Acquisition Directorate

Research & Development Center

Report No. CG-D-08-09

Heavy Oil Detection (Prototypes) Final Report

Distribution:

Approved for public release; distribution is unlimited. This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161.

June 2009

Homeland Security

N O T I C E

This document is disseminated under the sponsorship of the Department of Homeland Security in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

This report does not constitute a standard, specification, or regulation.

Timothy R. Girton
Technical Director
United States Coast Guard
Research & Development Center
1 Chelsea Street
New London, CT 06320-5506

Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-08-09		

4. Title and Subtitle	5. Report Date
Heavy Oil Detection (Prototypes) - Final Report	June 2009
	6. Performing Organization Code Project No. 4153
7. Author(s) Kurt A. Hansen; Michele Fitzpatrick; Penny R. Herring; Mark VanHaverbeke	**8. Performing Report No.** R&DC UDI # 827

9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
Potomac Management Group, Inc. a Division of ATSC 7925 Jones Branch Drive McLean, VA 22102	U.S. Coast Guard Research and Development Center 1 Chelsea Street New London, CT 06320-5506	**11. Contract or Grant No.** HSCG32-04-D-R00005 HSCG32-09-J-000085

12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered
U.S. Department of Homeland Security United States Coast Guard Commandant (CG-5332) Washington, DC 20593-0001	Interim
	14. Sponsoring Agency Code Commandant (CG-5332) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&D Center's technical point of contact is Mr. Kurt A. Hansen, 860-271-2865, email: Kurt.A.Hansen@uscg.mil.

16. Abstract (MAXIMUM 200 WORDS)

Current methods for locating and recovering submerged oil spills are inadequate. Detection methods are often improvised on-scene, and recovery techniques are labor intensive and not always successful. The U.S. Coast Guard Research and Development Center has embarked on a multi-year project to develop a complete approach for dealing with spills of submerged oils. This report describes the assessment of detection techniques using sonar, laser fluorometry, real-time mass spectrometry, and in-situ fluorometry to locate oil sitting on the sea floor. Evaluation of four proof-of-concept devices was conducted at the Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT), now called The National Oil Spill Response Test Facility, in Leonardo, NJ, between November 2007 and February 2008. Further testing of two of these prototype devices, plus three additional detection systems, was conducted at OHMSETT in January 2009. This report contains the results of these tests and recommendations for Federal On-scene Coordinators when responding to spills of heavy oil (contained in Appendix E).

17. Key Words	18. Distribution Statement
Heavy oil detection, multi-beam sonar, fluorescence polarization	Approved for public release; distribution is unlimited. This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161.

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	74	

(This page intentionally left blank.)

EXECUTIVE SUMMARY

Even though heavy (sinking) oils have historically accounted for a small percentage of spills, environmental and economic consequences resulting from such a spill can be high. Heavy oils can sink and affect shellfish and other marine life in addition to causing closure of water intakes at water treatment facilities and power plants. Regardless of whether the heavy oil is near the surface, neutrally buoyant in the water column, or on the bottom, its recovery is difficult. The underwater environment poses major problems including poor visibility, difficulty in tracking oil spill movement, and colder temperatures, complicating containment and recovery. Developing effective methods and technologies suitable for this environment is a major challenge.

Current methods are inadequate to find and recover spills of submerged oil. Many of the detection approaches are ad-hoc and the recovery techniques very labor intensive. The U.S. Coast Guard (USCG) Research and Development Center (RDC) has embarked on a multi-year project to develop a complete approach for spills of submerged oils, including detecting and mapping the spilled oil (Stage I) and containing and recovering it (Stage II). Each Stage is itself a multi-phase effort. This report discusses the process and results for Stage I.

Phase I – Detection and Mapping Proof-of-concept

A Broad Agency Announcement (BAA) was used to identify several potential submerged oil detection and mapping technologies in the proof-of-concept phase of development. Four companies were chosen to develop proof-of-concept instruments, which were then tested for the ability to locate and identify test patches of three types of heavy oil in sediment trays deployed in the Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT), now called The National Oil Spill Response Test Facility. The technologies included sonar, laser fluorometry and real-time mass spectroscopy. Based on test results, two were selected for prototype development using technical requirements and the risks associated with further development. The companies selected were EIC of Norwood, MA (fluorescence polarization) and RESON, Inc. of Goleta, CA (multi-beam sonar combined with data-processing software).

Phase II – Prototype Test Results

The configuration of the prototype tests, conducted at OHMSETT, included four types of heavy oil, four types of sea bottom, and intermittently placed rocks and seaweed. The two companies selected in Phase I, EIC and RESON, returned to test their equipment. Three additional vendors, Biosonics, CodaOctupus, and SRI International, tested their detection equipment at OHMSETT as well (at no cost to the USCG) on the same test configuration.

EIC returned to OHMSETT with a compact unit but bright sunlight during these tests saturated the instrument with strong backscatter. On-scene modifications allowed EIC to continue the tests and achieve usable results. EIC later developed a successful method to reduce the external light by modulating the laser and looking for the returned fluorescence that was also modulated. Due to the fluctuations of the GPS input, a direct mapping of the results was not possible.

The RESON prototype included a detection algorithm that uses backscattering strength to estimate oil patch location and size. While not done in real-time, the data transfer and calculations were completed for the entire test section in less than one day for the 400 kHz runs. While it was relatively easy to discriminate oil

from the bottom, the probability of detection can be increased as more information is known about specific oils and their properties and entered into the model. The system detected 87 percent of the target areas but had 24 percent false alarms.

BioSonics, Inc. (Seattle, WA) tested a unit equipped with two single-beam sonar transducers (200 kHz and 420 kHz) that are usually used to classify substrate (sub-bottom) or submerged vegetation. The system was successful in classifying the oil as a different kind of material in real-time. It was also able to differentiate the four types of bottom material that were used.

The CodaOctopus (New York, NY) EchoScope4D Imaging sonar operating at 375 kHz was tested. This is the same system that the USCG is evaluating for other uses. Like the RESON system, it uses return signal to differentiate between rocks, bottom, and oil. At almost all angles and frequencies, the contrast between oil and sand is about 15 dB. It also records and can display the bathymetry.

SRI International (Menlo Park, CA) was externally funded to evaluate a real-time mass spectrometer that has been used to map the field of a sewage outfall among other things. No oil was detected during tests in the large tank, but the system was able to detect low-level components in a set-up similar to the Phase I Woods Hole Oceanographic Institution (WHOI) configuration.

Conclusions and Recommendations

The technologies discussed in this report represent an improvement over the existing sunken oil detection methods. Although these systems have not been tested in the difficult harsh environment of low visibility, they may be useful immediately in some situations. This use could reduce the amount of effort currently required and increase reliability of oil detection on the bottom or in the water column.

The multi-beam and imaging sonars appear to be the best sensors to conduct wide area detection surveys. Some of the signal return issues, which can cause false positive detections for the low grazing angles of common side-scan sonar, are reduced in the tested systems. Most of these types of systems should be able to automatically detect large clumps of oil, but the resolution for widely dispersed product is still not complete. The sooner that a system is deployed before the oil breaks up, the better chance that detection will occur. Spill responders should ensure that detection equipment has some type of processing software to interpret raw sensor data.

The laser systems and narrower beam sonars may be better suited as a follow-up to the areas scanned by the wide scan sonars. These should provide better resolution and should be able to calculate general thickness, which could provide some information about the amount of oil. The narrow areas covered could introduce resolution issues, especially for widely scattered oil. On the other hand, the narrow area covered could be advantageous for guiding recovery efforts.

The real-time mass spectrometry systems should be evaluated for neutrally buoyant oil detection in the water column. For some spills, especially those in rough waves or fast moving currents, these instruments may be useful as mounted sensors in a fixed place. This would be especially useful for municipalities and power plants that use the water for cooling.

The use of this equipment by a Federal On-scene Coordinator (FOSC) is limited at this time due to the level of development. Guidance is contained in the Appendixes that provide information about the specific technologies tested. A decision-tool and recommendations for FOSC use are contained in Appendix E.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AUV	Autonomous underwater vehicle
BAA	Broad Agency Announcement
BS	Backscattering strength
cm	Centimeter(s) (10^{-2} meters)
cP	Centipoise
dB	Decibel(s)
EIC	EIC Laboratories, Inc.
FOSC	Federal On-scene Coordinator
FP	Fluorescence Polarization
g/ml	Grams per milliliter
GPS	Global Positioning System
HFO	Heavy fuel oil
IMO	International Maritime Organization
kHz	Kilohertz (1000 cycles/second)
LLSS	Laser Line Scan System
m	Meter(s)
mm	Millimeter(s) (10-3 meters)
MMS	Minerals Management Service
MS	Mass spectrometer
g/l	Micrograms (10-6 grams) per liter
nm	Nanometer(s) (10-9 meters)
No.	Number
OHMSETT	Oil and Hazardous Material Simulated Environmental Test Tank, now called The National Oil Spill Response Test Facility
OPRC-HNS	Oil Pollution Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances
PAH	Polyaromatic hydrocarbons
PMT	Photomultiplier tube
POC	Proof-of-concept
RDC	USCG Research and Development Center
RFI	Request for Information
ROV	Remotely operated vehicle
SAIC	Science Applications International, Inc.
TETHYS	TETHered Yearlong Spectrometer
TS	Target strength
UIS	Underwater Inspection System
USCG	U.S. Coast Guard
UV	Ultraviolet
V-SORS	Vessel-Submerged Oil Recovery System
WHOI	Woods Hole Oceanographic Institution

(This page intentionally left blank.)

1 INTRODUCTION

1.1 Background

Increased consumption and transportation of oil and its products increase the problem of pollution in lakes and oceans. Even with strict rules and regulations on oil transportation, accidents leading to oil spills still occur frequently, with thousands of tons of oil being spilled into seas. This results in the contamination of marine environments and endangers marine ecology. It is evident that oil spills in coastal waters, harbors, and oil terminals are especially dangerous and necessitate fast response in order to prevent contamination of marine habitats when such accidents occur. Therefore, reliable response systems for all types of oil spills and all environments are needed.

Locating and identifying heavy oil is a problem of growing concern as the use of heavy oil and related slurry products becomes more prevalent. In addition, even though heavy (sinking) oils have historically accounted for a small percentage of spills, environmental and economic consequences resulting from such spills can be high. Heavy oils can sink and affect shellfish and other bottom dwelling marine organisms, in addition to causing closure of water intakes at industrial facilities and power plants in both salt and fresh water. The underwater environment poses major problems for spill detection and response, including poor visibility, difficulty in tracking oil spill movement, and cold temperatures, all of which complicate containment and recovery. Developing effective methods and technologies suitable for this environment is a major challenge.

Numerous papers have been written about techniques to detect and recover oil sitting on the sea bottom. In early papers, authors focused on what conditions are required for oil to sink (Michel and Galt, 1995) or what should not be done (Castle et al., 1995). Others addressed specific recovery processes (Elliott, 2005 and Schnitz and Wolf, 2001). The International Maritime Organization (IMO) sponsored a forum in 2002 during which monitoring, modeling, and recovery of heavy oils were addressed (Brown, et al., 2002, Parthiot, Cabioc'h, 2002). The USCG RDC attempted to build on the efforts of Environment Canada (Brown et al, 2004 and 2006) by investigating an airborne laser fluorosensor to detect submerged oil (Fant and Hansen, 2005 and 2006). At least one underwater laser fluorometer system had previously been deployed (Barbini et al, 2000), although it had not been designed for detecting submerged oil. For the purpose of this report and following the Coastal Response Research Center (2007) definition, "submerged oil" describes any oil that is not floating at or near the surface. "Sunken oil" describes the accumulation of bulk oil on the seafloor.

After the major spills in the U.S. of the M/T Athos in 2004 in the Delaware River and T/B DBL-152 in 2005 in the Gulf of Mexico, the RDC decided to re-examine heavy oil response efforts (Michel 2006). At least one other commercial effort was pursuing a recovery method at that time (Usher, 2006). Parallel efforts by international organizations (Parthiot, 2004) were also ongoing. A workshop, co-sponsored by RDC in December of 2006, also reemphasized research needs (CRRC, 2007).

There is also an ongoing effort within the IMO Oil Pollution Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS) Working Group for Submerged Oils, headed by Italy.

1.2 Purpose/Objective

The U.S. Coast Guard (USCG) and industry do not have a consistent and reliable method to recover submerged oil on the sea floor, a task that includes the multiple phases of detecting, tracking, containing, and ultimately recovering submerged oil. Response to spills of heavy oils is often ad-hoc, with detection and removal strategies developed at the time of the spill. These methods are generally inadequate to find and recover the oil, and the recovery techniques are very labor intensive. The USCG needs to develop a blueprint for method(s) within the oil response industry to recover heavy oil located on the sea floor. To assist in this effort, the USCG Research and Development Center (RDC) has embarked on a multi-year project to develop a complete approach for response to spills of submerged oils, including detecting and mapping the spilled oil (Stage I) and containing and recovering it (Stage II).

The objective of the first stage is to identify and develop technologies capable of detecting heavy oil on the sea floor. The ability to detect, track, delineate, and quantify heavy oil on the sea floor will permit operational decisions to be made regarding feasibility of and best strategy for recovery. This report covers the results of the heavy oil detection and mapping research.

The long-term objective for the second stage of this effort is to create a system that will recover heavy oil from the sea floor. Such a system will have to accomplish a variety of tasks to be successful. These include detecting the oil, possibly concentrating/corralling the oil for collection, and collecting the oil into a containment vessel for proper disposal. The proofs-of-concept and prototypes that are developed will not be USCG-owned. They will be owned by industry and available for use if directed by the USCG to recover heavy oil. These are expected to be incorporated into response plans in the future.

1.3 Technical Approach

The identification of potential technologies was accomplished using a Request for Information (RFI) and a Broad Agency Announcement (BAA). The RDC released an RFI in the summer of 2006 asking vendors to provide potential approaches for the detection and recovery of oil on the sea floor. A summary of past experiences, especially with respect to the two latest spills (Michel, 2006), was provided as part of the RFI. RDC received responses to the RFI from 15 organizations, some of which addressed several topic areas. The five major topics addressed in the responses to the RFI were:

- Detection of Oil in the Water Column,
- Detection of Oil on the Bottom,
- Containment of Suspended Oil/Protection of Water Intakes,
- Containment of Submerged Oil on the Bottom, and
- Recovery of Submerged Oil on the Bottom.

The range of costs in the responses indicated that the project would need to proceed in stages. If a reliable detection technique can not be developed, then a major research effort should not be mounted for the recovery part of the process. As a result of the information submitted, it was decided to divide the research effort into detection (Stage I) and then recovery (Stage II).

In April of 2007, RDC published a BAA that requested approaches for detection only. The objective of the specification in the BAA was that the sensors should provide enough information for decision-makers to determine if an amount of oil sufficient to merit recovering could be identified. The approach was to divide the BAA process into a proof-of-concept phase (Phase I) where three to five vendors would be awarded contracts, and then a prototype development phase (Phase II) where two to three vendors would be awarded contracts. Two sets of performance requirements were listed, one for immediate verification for the concepts and one for the prototypes. Four technologies were selected for proof-of-concept testing in Phase I. From these, two proof-of-concept technologies were later selected for further prototype development and testing in Phase II. That selection was based on the technical requirements as well as the risks associated with further development.

1.3.1 Performance Requirements

For a successful proof-of-concept, the BAA requested the following capabilities for the detection technology:

1) Able to identify the presence of heavy oil on the sea floor with 80 percent certainty.
2) Able to detect oil on the bottom from at least 1 meter (m) (3.28 feet (ft)) away.
3) Oil location shall be geo-referenced to 1 m (3.28 ft) in accuracy.
4) Ideally, will provide real-time data, but at a minimum shall produce results and data interpretation hourly.
5) Able to provide data for all sea floor conditions (i.e., silty, rocky, and gravel bottom types; vegetation and shellfish-covered bottoms; and over flat and sloped areas and areas with rapid substrate changes). Phase I testing will be of simple sea floor conditions (i.e., flat and scattered protrusions).
6) Operate in fresh and sea water conditions equally well.
7) Operate in water depths of up to 33.3 m (100 ft).
8) Have minimal maintenance requirements (easy to maintain and calibrate).
9) Easy to operate and involve minimal training.
10) Easily de-contaminated and durable.
11) Equipment operation not adversely affected by exposure to oil.

Once the proof-of-concept has been demonstrated, the prototype device (or combination of devices) should be able to operate in the following conditions:

1) Able to search a one square mile area in a 12-hour shift.
2) Operate in water current of up to 1.5 knots.
3) Operate in up to 5-foot seas.
4) Operable during the day and night.
5) Able to be set up within 6 hours of arriving on site.
6) Easily deployable and transportable. Capable of being deployed from a vessel of opportunity and a variety of other platforms (i.e., towed bodies, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and manned submersibles).

1.3.2 Phase I Proof-of-concept Testing

The proof-of-concept (POC) testing permitted RDC to determine if the proposed technologies that are being adapted from other areas can actually be used to find oil. For the Phase I proof-of-concept evaluation, four vendors were selected:

- RESON: Multi-beam Sonar.
- Science Applications International Corp. (SAIC): Laser Line Scan System (LLSS) adapted for fluorescence.
- EIC Laboratories: Fluorescence Polarization.
- Woods Hole Oceanographic Institution (WHOI): In-Situ Mass Spectrometry and In-Situ Fluorometry.

The systems were tested at the Department of Interior Minerals Management Service (MMS) Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT), now called The National Oil Spill Response Test Facility, in Leonardo, NJ between November 2007 and February 2008. Section 2 of this report contains the discussion and results of the Phase I proof-of-concept testing.

1.3.3 Phase II Prototype Testing

Two of the systems from Phase I were selected for prototype testing at OHMSETT. They were: RESON Multi-beam Sonar and EIC Laboratories Fluorescence Polarization. Three additional vendors, Biosonics, CodaOctupus, and SRI International, tested their detection equipment at OHMSETT as well (at no expense to the USCG). Section 3 contains the discussion and results of the Phase II prototype testing. The Appendices contain supporting information.

2 PHASE I PROOF-OF-CONCEPT TESTING

2.1 Overview

The facility chosen for the heavy oil detection POC testing was MMS OHMSETT in Leonardo, NJ. The RDC believed that OHMSETT could provide a somewhat realistic environment while providing the ability to create targets and sufficient area to address the multiple aspects of each type of approach. Of the 11 capabilities for a successful POC listed in the BAA (see Section 1.3.1), the following could potentially be demonstrated at OHMSETT:

- Able to identify the presence of heavy oil on the sea floor with 80 percent certainty.
- Able to detect oil on the bottom from at least 1 m (3.28 ft) away.
- Oil location shall be geo-referenced to 1 m (3.28 ft) in accuracy.
- Ideally, will provide real-time data, but at a minimum shall produce results and data interpretation hourly.
- Able to provide data for all sea floor conditions (i.e., silty, rocky, and gravel bottom types; vegetation and shellfish-covered bottoms; and over flat and sloped areas and areas with rapid substrate changes). Phase I testing will be of simple sea floor conditions (i.e., flat and scattered protrusions).

Vendor ability to meet the other POC performance requirements was determined by RDC discussions with vendors and review of materials they provided.

2.1.1 Test Set Up

Three of the four systems were tested in OHMSETT's large outdoor tank (see Figure 1). Because of the time of year of the testing (winter) and the nature of the sensors, the system from WHOI was tested in an inside tank (described in Section 2.5). The OHMSETT facility provides an environmentally safe place to conduct objective testing and to develop devices and techniques for the control of oil and hazardous material spills. Appendix A gives more details about the OHMSETT facility.

Figure 1. OHMSETT test facility.

The large test tank at OHMSETT is an above-ground concrete tank measuring 203 m (665 ft) long by 20 m (66 ft) wide and 3.4 m (11 ft) deep. At the time of testing, however, the water depth was reported as 2.4 m (8 ft). The test tank is equipped with a tow bridge that spans the width of the tank and moves along the tow length at speeds of up to 6.5 knots. The bridge is outfitted with a climate-controlled laboratory space to accommodate personnel, computers, bridge motion controls, and other components sensitive to the elements. The salinity in the tank during the tests was 26 parts per thousand.

2.1.2 Oil Selection and Sinking Oil

The first major challenge in the proof-of-concept testing was to determine how to create stable oil targets under water. The two oils selected were Sundex 8600, a heavy oil used by OHMSETT, and Number (No.) 6 fuel oil (also known as Bunker C or heavy fuel oil (HFO)). Due to the specific gravity of the test oils relative to the tank water, barite ($BaSO_4$) was incorporated in the oil samples to increase their bulk density to ensure the samples would be heavier than the tank water and that the samples would remain deposited within the test trays throughout the study period. Figure 2 shows the chart used to determine the amount of barite needed to ensure that the densities of the oils were heavier than the water, about 15 percent by weight.

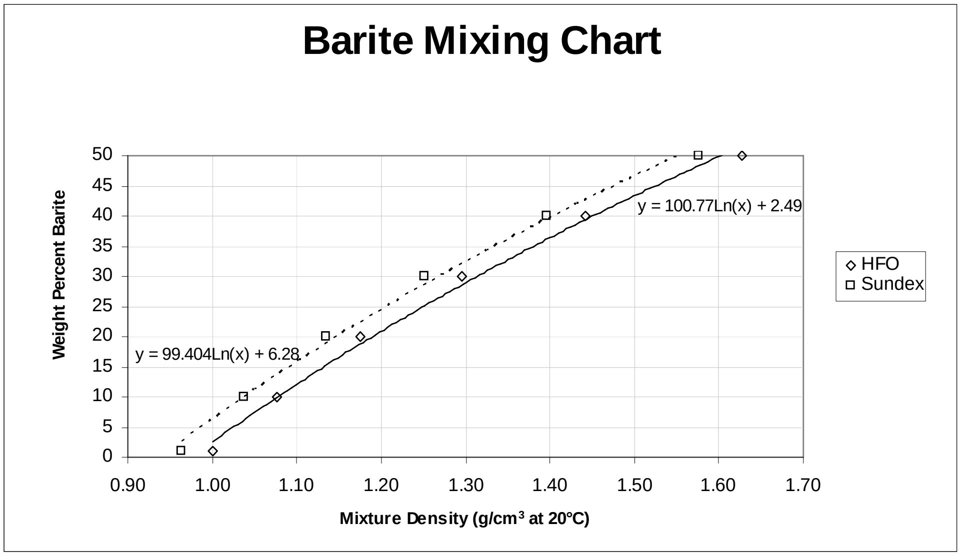


Figure 2. Chart for calculating oil/barite density.

2.1.3 Test Trays

Two test trays were constructed to hold the oil at the bottom of the OHMSETT tank. Each was fabricated from aluminum and measured 2.4 m by 2.4 m (8 ft by 8 ft). One tray had a 15.24 cm (6 inches) lip and the other a 20.32 cm (8 inches) lip. The trays were filled with construction sand and then depressions were made for false targets and oil-filled locations (see Figure 3a). Both types of oil and a piece of roofing tar were placed in their respective locations along with some false depressions. The targets were 1-3 inches thick and 2-3 ft in diameter. The trays were filled with water to saturate the sand and moved to the bottom of the OHMSETT main tank (see Figure 3b). Over time, sediment settled on some of the targets.

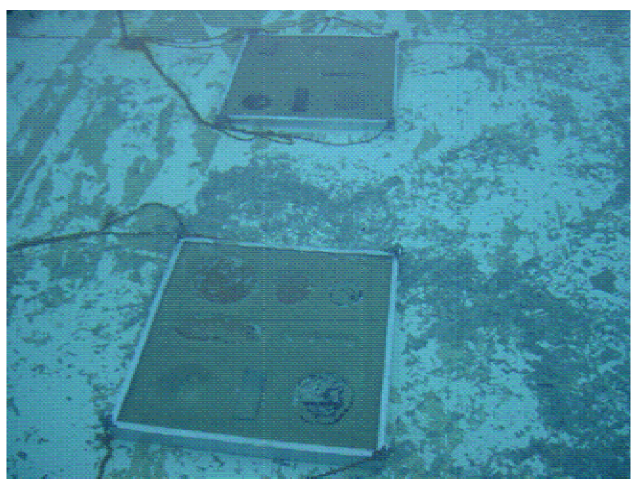
(a)  (b) 

Figure 3. Test trays (a) before placing into tank and (b) on tank bottom.

2.2 RESON, Inc. 7125 SeaBat System

2.2.1 SeaBat System Description

The SeaBat 7125 system is a dual-frequency multi-beam echo sounder (sonar) designed to measure relative water depths over a wide swath perpendicular to the towing vehicle's track. It can operate at either 200 kHz or 400 kHz. For the POC test, the sonar was connected to RESON PDS2000, a software package designed for hydrographic survey and dredging operations. Figure 4 shows the components of the SeaBat system. According to the manufacturer, the SeaBat 7125 ensonifies a 128 degree sector below the sonar head assembly and is suitable for mounting on a surface vessel, ROV, or AUV.

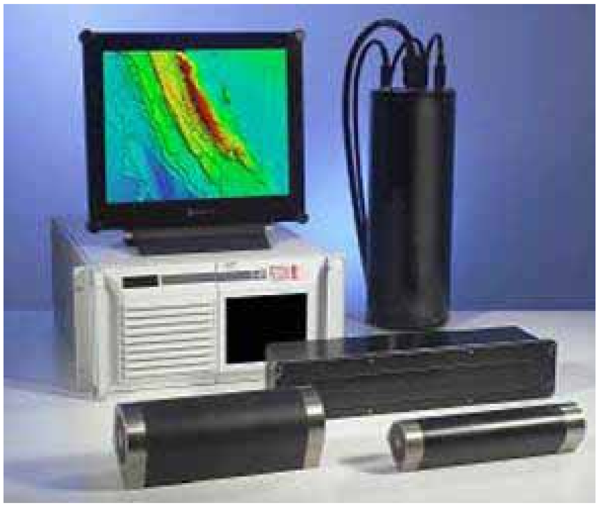


Figure 4. RESON 7125 SeaBat system.

The theory for the acoustic detection of oil is that the oil would be less reflective than the sand. On the sonar image, the less reflective material is represented as darker shades on the display and the more reflective material is displayed in lighter shades. Appendix B gives a more detailed discussion of the acoustic detection of heavy oil.

2.2.2 SeaBat Test Description

The Phase I POC demonstration focused on the sonar capability to detect the oil sample by visual inspection of the acoustic image and simple thresholding. The SeaBat POC test was carried out at the OHMSETT test facility on 28 November, 2007. The sonar head was installed rigidly on a pole that could be moved across the bridge spanning the width of the tank (see Figure 5). The sonar was placed just below the water surface, 2 m (6.6 ft) above the bottom of the tank (see Figure 6). The bridge moved along the tank at speeds ranging from 0.1 to 6.0 knots. The test conditions simulated a very calm sea. The wind did not affect the test, and no rain or other source of acoustic noise was present.

Figure 5. RESON 7125 SeaBat system mounted on the OHMSETT tank.

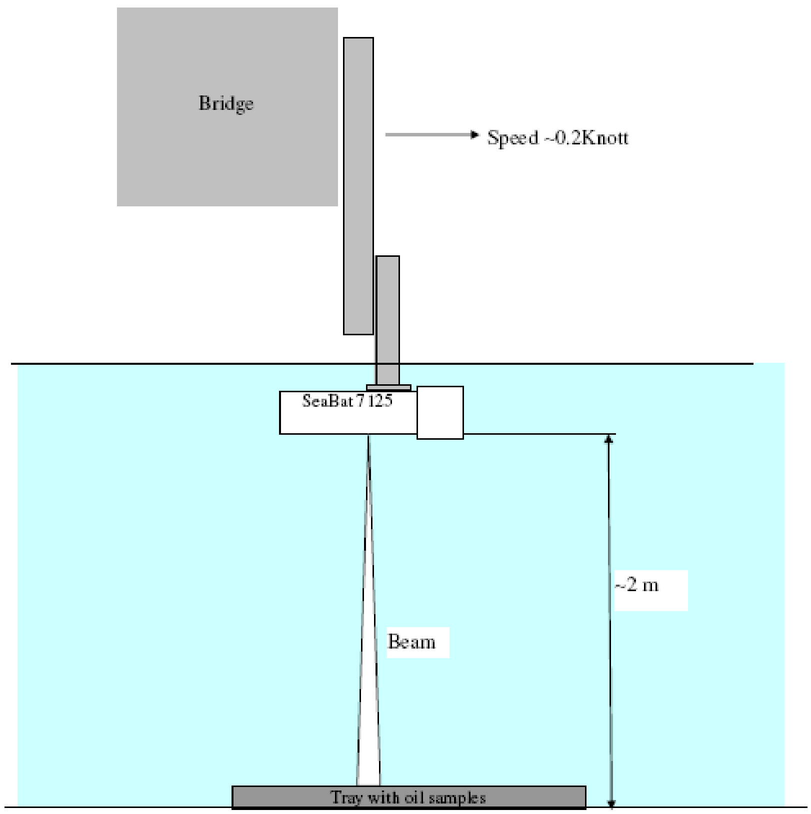


Figure 6. Set-up of SeaBat in OHMSETT tank.

The sonar was set to operate in a normal survey mode and the bridge simulated a vessel. The sonar was moved laterally across the width of the bridge to test the effective swath of the system. The system was primarily operated at 400 kHz; however, two test runs at 200 kHz were also conducted.

2.2.3 SeaBat Results

The sonar was moved over the targets several times, with most runs performed at a frequency of 400 kHz. The very high ping rate of the system and the short range dictated by the test set-up provided plenty of data for detection. All targets (Sundex, No. 6 oil, and asphalt) were positively detected, as each of the samples appeared clearly on the monitor as dark areas against a brighter background. This was the expected result, given the low acoustic reflectivity of oil compared to that of typical seabed sediment. Figure 7 gives an example of the SeaBat results.

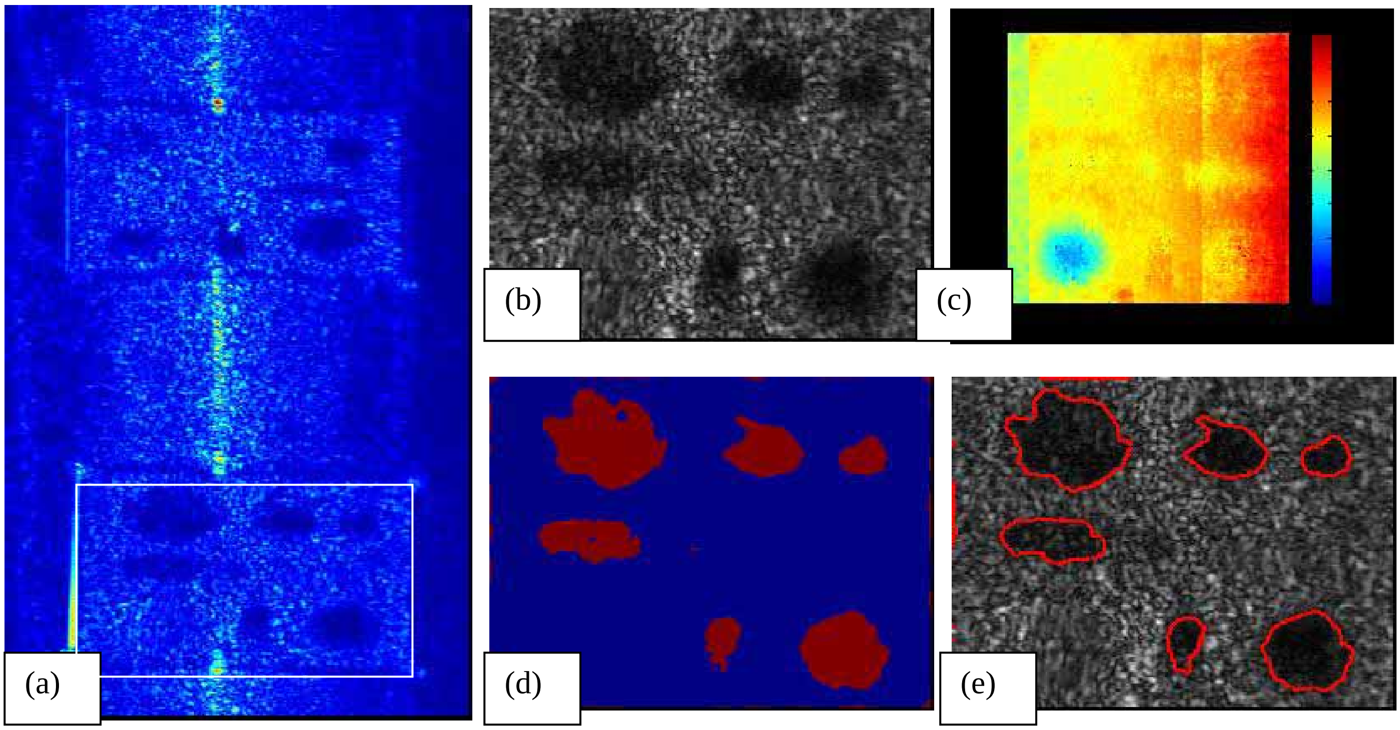


Figure 7. RESON SeaBat sample results.

The left portion of Figure 7 (a) shows the raw intensity data collected while the sonar was traveling over the tray. The top center image (b) is a zoom on the data being processed (bottom tray in figure on left, area inside white rectangle). The top right image (c) shows color-coded bathymetry results provided by the multi-beam echo sounder. The bottom center image (d) shows the automatic detection results and the bottom right image (e) shows the outline of the detected objects overlaid on the raw intensity data.

All targets present in the sonar swath were positively detected with a probability exceeding 80 percent, with the exception of one target. That target was properly segmented as oil, but the detection process merged it with the tray walls. On this target, the detection rate was 75 percent. The same target oil in the other tray was detected with a rate of 85 percent. The processing parameters were kept constant for all the runs. The process generated one false alarm on a blank target. This represents an overall false alarm rate of 8 percent.

2.2.4 SeaBat Next Steps

The POC test showed that a trained operator can visually detect the patches representing heavy oil on flat, coarse, sandy sea floor with a high degree of certainty. A series of further experiments will be required to gather enough data for the development of a more robust solution involving software that can call suspicious areas to the attention of the operator.

The data collected during this exercise, as well as data collected by RESON at OHMSETT independent of this exercise, were used to develop an automated detection system that does not rely solely on the operator to visually detect the oil. The prototype system was expected to include an advanced image processing solution and a model inversion solution. These solutions would be based on measuring the backscattering strength as a function of multiple parameters, including the physical characteristics of the seafloor.

2.3 SAIC Laser Line Scan System (LLSS)

2.3.1 LLSS Description

The SAIC SM-2000 LLSS was originally developed as a reconnaissance tool for sea floor characterization and underwater search and recovery operations. This high-resolution survey tool was designed for the identification of substrate types, assessment of biological resources, and detection of hard targets on the seafloor. The optically-based system was originally developed to bridge the gap between underwater video and side-scan sonar by emitting a high-power, blue-green (532 nanometer (nm) wavelength) laser and reading the intensity of light reflected back to an internal receiver at that wavelength.

Although the system provides an excellent light source for imaging the seafloor and gathering data based on light reflectance, the blue-green laser was not considered the optimal light source for exciting deposits of oil on the seafloor. As a result, SAIC incorporated a lower wavelength, higher energy laser light source that approached the ultraviolet-A (UV-A) band (405 nm) to exploit the fluorescent properties of heavy oil and develop an accurate submerged oil detection tool. Appendix C discusses the optical and fluorescent detection of heavy oil in more detail. Although just above the UV-A band, the 405 nm laser was selected as the best option to elicit fluorescence underwater due to its ability to deliver a high amount of energy per photon while offering increased resistance to attenuation as it is transmitted through the water column.

Further modifications to the LLSS included the incorporation of precision optical filters to control the intensity and wavelength of light that entered the receiver unit. The filtering scheme was specifically designed to target the fluorescent response of oil-based compounds centered at 480 nm, which was determined to be the most advantageous starting point for the Phase I testing. Previous research had shown that crude oil responds to laser excitation from a low-wavelength light source over a broad range (400 to 650 nm), with peak intensity recorded in proximity to 480 nm. In addition, the filtering scheme was designed to eliminate the effects of light reflection associated with the 405 nm laser, as well as the potential of false positives based on the fluorescence of dissolved organic matter (420 nm) and chlorophyll-a (685 nm) in the water.

2.3.2 LLSS Test Description

Prior to the proof-of-concept testing at OHMSETT, SAIC conducted a dockside wet test of the LLSS in local waters (see Figure 8a). This test was conducted to better facilitate efficient POC testing, as well as to provide insight into possible interference or noise associated with fluorescence from other compounds in the natural environment. Representatives of RDC observed much of the wet test so they could see how the modified LLSS worked in a harbor environment.

(a)  (b) 

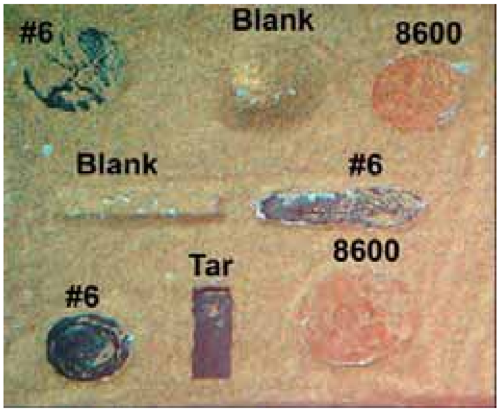
Figure 8. SAIC LLSS (a) being lowered over the side of a vessel and (b) mounted in the OHMSETT tank.

During the POC testing at the OHMSETT tank, the LLSS was suspended in water by a four-point harness system, which was secured beneath the moving bridge (Figure 8b). The bridge was then maneuvered to make multiple passes over the two test target trays during daylight, dusk, and darkness. Due to the relatively shallow water depth within the tank, the LLSS was positioned to scan the trays at an angle (approximately 30 degrees). This increased the focal distance between the LLSS and the test trays on the tank bottom to the minimum operating distance.

2.3.3 LLSS Results

During daylight conditions, the sunlight saturated the test area with the wavelength of light that the filtered receiver was designed to capture. As a result, the modified LLSS provided accurate imagery data (Figure 9a) but failed to elicit and/or detect any fluorescent signal over the background light.

The LLSS imagery acquired over the test trays during the night runs was essentially a monochromatic image with dark areas indicating zero to weak fluorescent return (Figure 9b). The brighter areas in the imagery, representing relatively intense return within the preferred bandwidth, were indicative of a response to the excitation laser at sufficient strength to pass through the filter. The scan angle of 30 degrees required by the test configuration resulted in a narrower swath than would be expected in field conditions. The outermost returns were out of sync, resulting in a darker image on one side of the swath. The intensity of the return signal suggests that the 10 nm band pass, 480 nm filter was adequate to capture the light emitted by the weathered Sundex 8600 oil deposits that were embedded within the sediment matrix (this is not obvious in Figure 9b due to the Sundex 8600 being in the area of no data in that image). In contrast, the fluorescent response of the No. 6 fuel oil and roofing tar deposits were present and detectable by the modified LLSS, but recorded at a much lower intensity.

(a) 

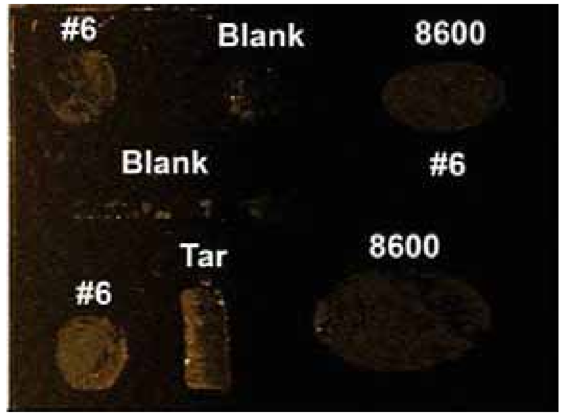
(b) 

Figure 9. SAIC LLSS sample results for (a) visual and (b) fluorescent wavelengths.

2.3.4 LLSS Next Steps

In general, the data obtained as part of the POC testing indicated that the modified LLSS could be an effective tool for the detection and mapping of heavy oils on the seafloor through fluorescence. However, the results also indicated that further refinement and experimentation with the laser technology would be required to fully satisfy the objectives of the research and development effort.

Due to the depth requirement and the light reflection off of the tank sides and bottom, this system cannot be fairly tested at OHMSETT again. The system needs a better way to improve signal/noise ratio to detect fluorescence. Possibilities include a more powerful laser and/or better processing. The following is a list of key elements of any future modifications and testing of the LLSS as a submerged oil deposit detection and mapping system.

1) *Limit ambient light* – The clear water and white epoxy paint in the OHMSETT test tank did not represent optimal conditions to conduct the testing. Future testing should be performed in an environment that better mimics conditions in a coastal harbor and/or port facility where sizable spills of heavy oil are more likely to occur.
2) *Increase the power of the laser light source* – Major considerations in the design of this optical tool are compensating for the attenuation of the 405 nm laser excitation light, as well as maximizing the intensity of the fluorescent response of an oil deposit. Even if dissipated somewhat by turbidity or dissolved organics, a higher intensity laser should increase the operational range of the LLSS and reduce the effects of suspended particulates and water color.
3) *Filtering* – The initial testing indicated some apparent differences in the intensity of the returns associated with each type of test oil, suggesting the current configuration of the laser light source and filtering scheme may be better suited to low molecular weight polyaromatic hydrocarbons (PAHs) relative to high molecular weight PAHs. Continued refinement of the modified LLSS through the alteration of the return light signal filtering scheme to allow the passage of a broader spectrum of visible light, inclusive of the green and red color range, is likely to improve the capability to detect a wider variety of heavy oil deposits on the seafloor.
4) *System Dimensions* – The results of the tank testing indicated that the minimum distance between sensor and target of 2.5 m and the sheer size and weight of the existing LLSS unit are limitations that need to be addressed as part of the future refinement of the LLSS as a oil detection tool.

2.4 EIC Laboratories Fluorescence Polarization (FP)

2.4.1 FP System Description

Fluorescence spectroscopy has been shown to be an effective tool for monitoring oil contaminants in water. Because the main constituents of oils are aromatic compounds, illumination of oil samples with ultraviolet or visible light causes the oil samples to emit fluorescence. Fluorescence-based methods have several advantages, including: they are non-contact, have high-sensitivity to the presence of aromatic hydrocarbons, and are easily miniaturized. There are other fluorescing species in marine environments however, such as humic compounds and chlorophyll, that may interfere with direct fluorescence measurements. In addition, ambient light interferes with fluorescence measurements and limits the use of fluorescence to night unless costly pulse excitation/detection schemes are used. One way to mitigate these problems and to enhance the selectivity of fluorescence is to incorporate polarization into the measurement technique. FP measurements are based on the assessment of the rotational motions of species. In particular heavy oils, which are very viscous, will show significant fluorescence polarization when excited with polarized light. Appendix C discusses the optical and fluorescent detection of heavy oil.

In EIC's system, a compact, continuous wave, green (532 nm), diode-pumped, solid-state laser is used for fluorescence excitation. Figure 10 shows the EIC FP system. The main components of the FP probe are the fiber optic fluorescence polarizer and a telescopic focusing/collection optic. The fiber optic fluorescence polarizer consists of three miniature optical trains (laser excitation, perpendicular FP collection, and parallel FP collection) arranged in a backscattering collection probe configuration. The probe telescope is a simple refractor telescope consisting of a 50 mm diameter, 100 mm focal length objective lens and a 9 mm diameter, 11 mm focal length eyepiece. The telescope is used to focus the laser beam into the sample and also to collect the fluorescence emitted by the sample. With the telescope as the front optics of the FP probe, the probe can detect fluorescence signals from fluorescent samples less than 1 m away from the probe to several meters away. The telescope focus is adjusted by moving the eyepiece between the polarizer and the objective lens. In the current POC probe, the eyepiece is moved manually; however, the eyepiece can be mounted into a linear actuator where the linear movement can be controlled via software and thus allow active focusing of the FP probe.

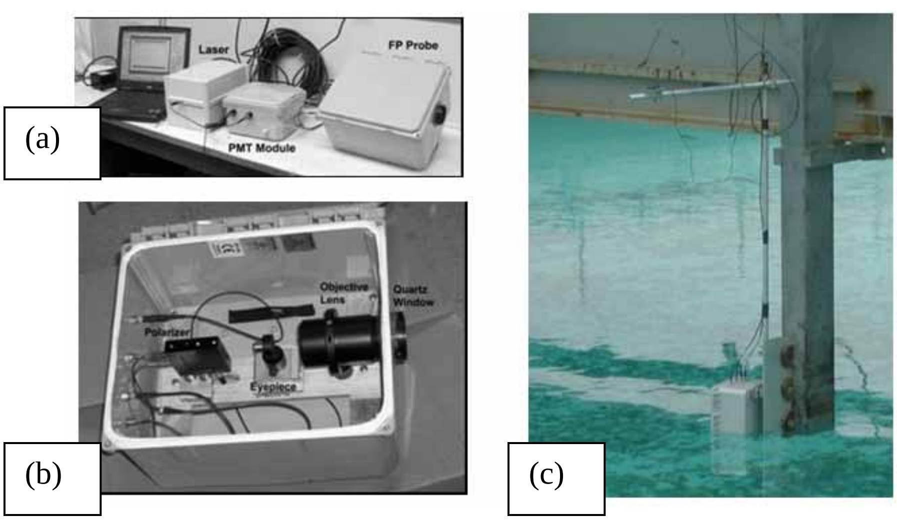


Figure 10. EIC FP system (a) on table top, (b) inside probe case, and (c) mounted on OHMSETT tank.

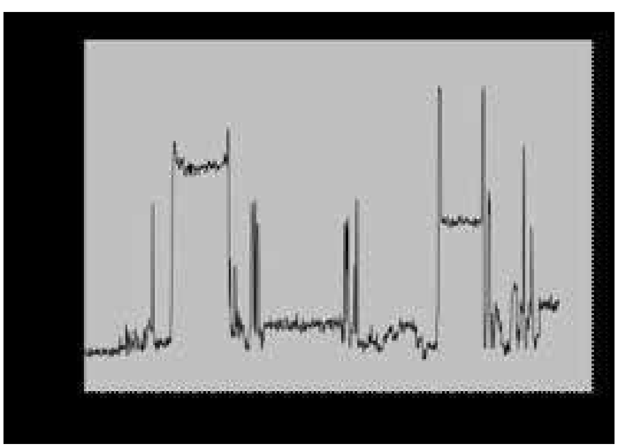
2.4.2 FP Test Description

After the FP probe and instrument were deployed from the tow bridge at OHMSETT, the first test was to determine whether the FP probe could detect the individual oil targets in the test trays. The FP probe was slowly scanned (0.5 knot speed) through each of the oil targets while the FP signal was continuously recorded. In some oil targets, the probe was stopped for a short time. Several strong polarization signals (>0.25) were observed during the scan, and these signals correspond to areas when the probe focus was on oil targets. In several of the targets, the oil samples were partially covered with sand. Even with these samples however, an FP signal was still detected.

FP grid scans of the test trays were also performed. To allow geo-referencing of the detected FP signals, a differential Global Positioning System (GPS) antenna was attached to the FP probe during the grid scans to record GPS coordinates that were then paired with the FP signals. Grid scans were started on one corner of the tray so that the first scan is about 0.67 m (2 ft) away from the edge of the tray. The tow bridge was moved from along the length of the tray, and at the end of each scan the probe was translated by about 15.24 cm (6 inches). The last scan was about one meter away from the other edge of the tray. The tow speed was kept constant during the scans.

2.4.3 FP Results

Test results of the POC fluorescence polarization instrument at OHMSETT indicate that the FP probe is capable of accurately detecting heavy oil in real time. Oil targets in the test trays showed significant FP signals that can be easily distinguished from ambient backgrounds such as sunlight or background fluorescence. Figure 11a shows the linear plot of a grid scan that was performed at a 1-knot speed. In this plot, it can be seen that several strong fluorescence polarization peaks were observed in the middle section of the graph, corresponding to the area when the probe was over oil targets. Figure 11b shows the GPS plot of the 1-knot speed grid scan and clearly shows the FP peaks in the center of the grid. Figure 12 shows the EIC FP results as a contour plot. All testing was done during daylight hours on cloudy to overcast days. No interference from sunlight was observed. Furthermore, it was determined during testing that the test tank surface paint fluoresces, but did not give a strong FP signal.

(a) 

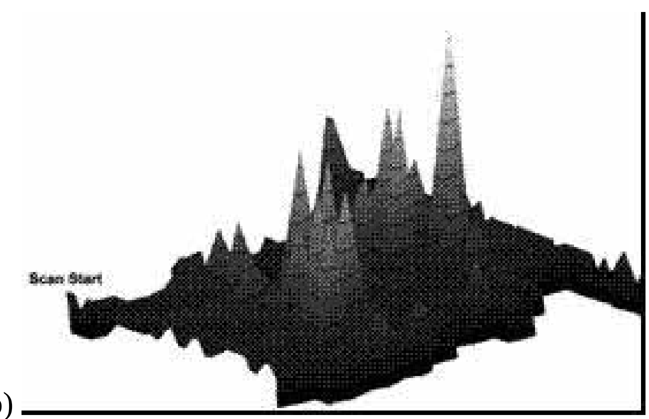
(b) 

Figure 11. Sample results from EIS FP showing (a) single line and (b) summary of all lines scanned.

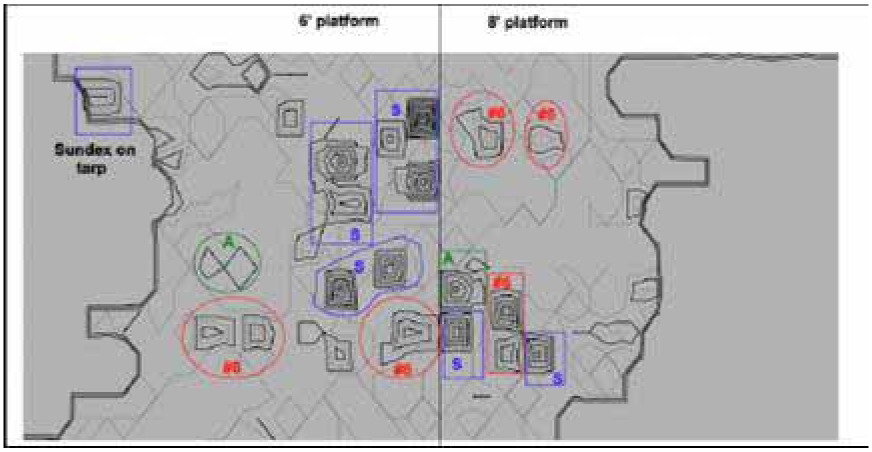


Figure 12. EIC FP contour plot.

2.4.4 FP Next Steps

The ultimate goal of this project is to develop an autonomous submersible fluorescence polarization detector for heavy oil that can be integrated with different types of deployment vehicles. To achieve this goal, the plan for Phase II was to miniaturize the components of the POC FP instrument, assemble them into a compact instrument, and encase them in a sealed tubular housing. The FP instrument should incorporate an embedded computer to allow the system to operate autonomously and communicate with the host vehicle.

2.5 Woods Hole Oceanographic Institution (WHOI) Detection and Identification System

2.5.1 WHOI System Description

The WHOI detection system relies on two complementary modes of hydrocarbon sensing: a TETHered Yearlong Spectrometer (TETHYS) mass spectrometer (MS) in combination with an off-the-shelf UV fluorometer. See Figure 13 for the WHOI system: (a) MS & fluorometer in waterproof housing, (b) suction hose and transducer, and (c) navigation system with three transponders. The TETHYS instrument is an underwater in-situ MS developed through a partnership between WHOI and Monitor Instruments LLC. The UV fluorometer (Chelsea Instruments Ltd., Surrey, England) is sensitive to aromatic hydrocarbons fluorescing at 360 nm. The TETHYS instrument is capable of identifying and describing hydrocarbon composition across a broad spectrum ranging from methane to tridecane, as well as halogenated hydrocarbons and many other toxic industrial chemicals. The instrument utilizes a proprietary non-evaporable getter ion pump and mass analyzer developed by Monitor, called the Miniature Mass Analyzer (MMA). One suction pump pulls the water into the instrument for sampling. Another pump and hose combination is used to spray the surface of the oil to get oil particles into the water column which the other system can sample.

(a) (b) (c)

Figure 13. WHOI system (a) MS & fluorometer in waterproof housing, (b) suction hose and transducer, and (c) navigation system with three transponders.

2.5.2 WHOI Test Description

2.5.2.1 Laboratory Sensitivity Study

Prior to the OHMSETT tests, WHOI conducted lab sensitivity tests with the two test oils used at OHMSETT. Based on these heavy oil samples, a series of molecular “fingerprints” of hydrocarbon constituents was developed with the TETHYS MS and UV fluorometer. These data were then used to develop mission scripts to monitor for specific hydrocarbon compounds with high signal-to-noise ratios. This resulting classification system optimized the MS’s operational parameters to track only relevant ion peaks, thereby improving the operational response of the MS. The aromatic UV fluorometer was operated in parallel during this sensitivity analysis to develop a composite limit of detection and response metrics for detection of heavy end members from these heavy oil types. Figure 14 shows the results of the sensitivity analysis (the vertical scale for the blue bars is MS ion counts and for the red bars is carbazole equivalent micrograms per liter (μg/l)). The system can detect trace amounts of specific compounds but it is not clear if the levels during testing would reach minimum values needed.

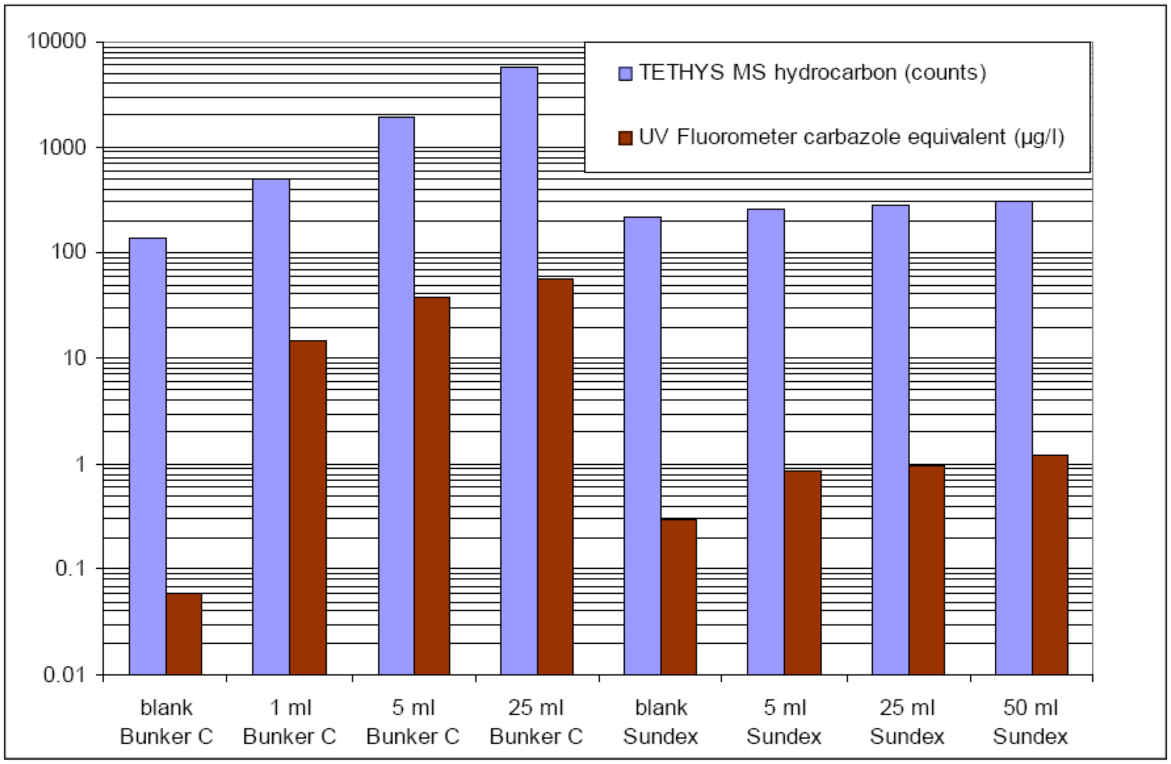


Figure 14. Results of WHOI lab sensitivity study.

2.5.2.2 OHMSETT Testing

The WHOI system was tested inside (in February) in a portable FasTank (3.05 m (10 ft) diameter, water about 0.965 m (3.2 ft) deep). WHOI used a short baseline transponder system that included a transducer at the end of the snorkel pole to position the system. Trial operations were conducted as three surveys, with TETHYS MS and UV fluorometer system operating from an aluminum platform directly above the test tank. An intake snorkel was moved through the water in a pattern consisting of four parallel tracklines, spaced with approximately 0.5 m separation and at a vertical distance of approximately 0.5 m above the tank bottom. During each grid survey, the snorkel was moved to and held at discrete waypoints (3 to 4 waypoints per trackline) while the MS and UV fluorometer measured the hydrocarbon levels at that position. The first survey was conducted as a negative control, without any hydrocarbons. The second survey, of similar geometry, was conducted with a hydrocarbon sample in the tank. The third survey was conducted after the hydrocarbon sample was repositioned in order to characterize the oil diffusion rate.

2.5.3 WHOI System Results

Analysis of the Sundex 8600 and No. 6 fuel oil samples indicate that the TETHYS MS is well suited to detect trace levels of volatile short-chain hydrocarbons (e.g., methane through octane), while the UV fluorometer is able to detect water-soluble aromatic hydrocarbon components (e.g., benzene, toluene, xylene, and naphthalene). Most heavy oil spills contain small but significant fractions of these volatile or water soluble petroleum fractions, making the MS and fluorometer combination highly useful for detecting heavy oil hydrocarbon contamination. Gas chromatographic analysis of the short-chain hydrocarbons from samples taken in parallel with TETHYS MS and UV fluorometer data suggest that even when undispersed (i.e., settled on the bottom and not disturbed), Sundex 8600 and No. 6 fuel oil both emit small but detectible

amounts of these light hydrocarbons into the water column. Furthermore, these sensitivity data suggest that because the flux rates are extremely low, plumes of these heavy oil tracers may persist at detectable levels in the water column for weeks to months in calm water.

Figure 15 shows sample results from the OHMSETT testing. Results from this research program suggest that common heavy petroleum product spills, including sinking fuel oils such as No. 6, can be located and identified through the use of light fractions as tracers using MS techniques. Low molecular weight aromatic compounds possessing high water solubility may also serve as tracers using UV fluorometry, although the addition of barite to oil samples appears to render this technique ineffective. It is unclear if turbulent mixing of the oil will improve UV fluorometer sensitivity.

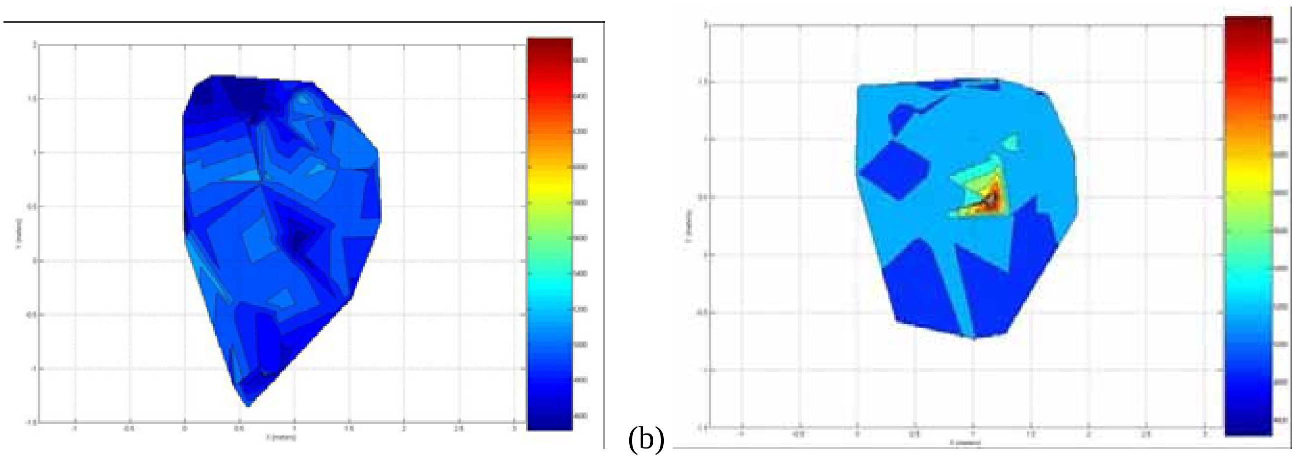

(a) (b)

Figure 15. Results of WHOI sampling in OHMSETT tank (a) before container of oil was added and (b) after oil was placed.

POC tank tests at the OHMSETT facility have demonstrated that plumes of light tracer compounds (methane through butane) readily diffuse from sunken oil sources and persist with sufficient intensity over time to be detected using the TETHYS mass spectrometer. This technique is valid at distances greater than 1 m with better than 80 percent accuracy under the conditions tested. Furthermore, by combining this sensory technique with high precision acoustic navigation, intensity contour plots can be constructed that accurately characterize the source location and spatial extent. It is not clear, however, if the oil will actually release components into the water column and what their movement will be in even a small amount of current. In addition, the sensor may have to be deployed very close to the bottom, which could be problematic, especially for rough bottoms.

2.5.4 WHOI System Next Steps

To improve the system, the TETHYS components could be optimized to improve their spectral resolution and sensitivity to the oil fractions identified in the fuel oil. Information regarding the behavior of other submerged oils, whether through models or experimentation, would be needed to further refine the system.

This system is already being used in the Gulf of Mexico. A recent hurricane caused an underwater avalanche that buried some oil pipeline. To relocate the pipeline, a water jetting tool was used to disturb the upper layer of the silt, and the WHOI system was then used to sample the water column for hydrocarbons. The process was successful in mapping the bottom that was saturated with oil.

2.6 Phase I Summary of Results

2.6.1 Test Set-up Considerations

As discussed in Section 2.1, OHMSETT was considered to be the best facility for conducting the POC tests. Not all of the BAA performance requirements could be tested at this facility. Some capabilities, such as the ability to operate equally well in fresh and sea water, needed to be determined independent of the OHMSETT tests.

There were some other issues resulting from the limitations of the test set-up. The relatively small tray areas as compared to the swath width of the instruments caused problems for some of the instruments during this round of evaluations. In addition, it was not clear in the beginning if the silt in the tank would influence results.

2.6.2 POC Test Results

The testing objective was met and the proof-of-concept evaluation was successful. All four of the systems located oil under the conditions that were given; that is, clear water with a limited amount of turbidity or sand covering the oil. Table 1 gives a summary of the test results compared to the BAA performance requirements listed in Section 2.1.

RESON is adapting an existing system. Although sonar systems have been used in the past to locate submerged oil, the issue of concern is the turn-around time of the interpretation, and RESON appears to be addressing that issue. It is not clear how this system will perform in muddy bottoms where the difference in density between the oil and bottom is closer than the conditions documented in this test.

The SAIC system is adapted from an existing system and appears to work in low light conditions – again given reasonable clarity. Additional refinements were recommended for any additional efforts. Any future tests should take place in a more realistic environment so that the light levels and focal length are in line with the system performance, as these conditions cannot be met in a controlled tank environment.

The EIC equipment is a new approach and while it may have more risk than the other systems, it also may have the most applicability. The small size of the equipment may lend its applications to multiple uses, including mounting in small ROVs or AUVs. It also may be small enough to be mounted on a suction head during recovery operations.

The WHOI system has already been used to detect some oils in a calm water column and it appears the approach could be refined depending upon the oil spilled. The sinking mechanism for the spill must be such that the lighter components of the oil are still available, such as fuel oil that mixes with sand. But it is not clear how much dissolved or particulate oil would be in the water column under more realistic circumstances, especially after several days or weeks or with current flow. Predictive models of heavy oil are not currently available for that scenario.

Table 1. Phase I test results.

Requirement	RESON	SAIC	EIC	WHOI
Identification of heavy oil on sea floor (80% certainty)	The detection rate was 100% on most of the targets. It was at least 80% on all targets.	Poor response in daylight detection of ambient light. Better results at night.	Yes [certainty not listed in report].	Both oils tested were detected in the water column in the limited configuration.
Ability to detect oil on the sea floor from at least 1 meter away	The detection range was only limited by the tank geometry. The longest detection range was 4 m.	Focal length of the laser was longer than the depth of the tank. Should be able to meet.	Can detect signals from fluorescent samples <1 m away from the probe to several meters away.	No, uses very close-in sampling technique.
Georeference oil locations	If the tank facility is located outdoors and a valid Differential GPS track is obtainable then the oil targets could possibly be geo-referenced as part of the tank test.	Done with previous system.	Software for the data acquisition board allows a GPS signal to be recorded along with the FP signals for geo-referencing.	Real-time position estimate of the hydrocarbon sample was accomplished using a 150 kHz long baseline navigation system.
Real time data	The POC system had a real-time display, but needs work to produce real-time analysis.	Can view from screen with additional coordination with locations needed.	Detection display available in real-time. Contour plots require a grid scan and data processing.	Generally yes, but not clear if covering a large area.
Operate in fresh and sea water conditions equally well	Tested in sea water only but no impediments noted.	Tested in sea water only but no impediments noted.	Tested in sea water only but no impediments noted.	Tested in fresh water only but no impediments noted.

The technologies represented here are an improvement over the existing ad-hoc methods. Although these systems have not been tested in the difficult harsh environment of low visibility, they may have immediate use in some situations, for which they could reduce the amount of effort and increase reliability of oil detection on the bottom or in the water column. T

The amount of available funding limited selection to two choices for Phase II prototype development. Since the WHOI system was not able to reliably detect the oil from 1 meter away, it was eliminated from future testing. The SAIC system was large and could not be adequately evaluated in the shallow confines of the Ohmsett tank. In addition, unacceptably high risks are associated with the large amount of work needed for further development for the SAIC system; so it was also eliminated from further testing. The other two systems showed more capabilities when used in combination; so they were chosen for further evaluation.;. The next step was to complete prototype development and evaluate the RESON sonar and EIC fluorosensor at OHMSETT in a more realistic environment.

3 PHASE II PROTOTYPE TESTING

3.1 Overview

As discussed in Section 1.3, the BAA requires that the prototype device (or combination of devices) shall be able to operate in the following conditions:

1) Able to search a 1 square mile area in a 12-hour shift.
2) Operate in water current of up to 1.5 knots.
3) Operate in up to 5-foot seas.
4) Operable during the day and night.
5) Able to be set up within 6 hours of arriving on site.
6) Easily deployable and transportable.
7) Capable of being deployed from a vessel of opportunity and a variety of other platforms (i.e., towed bodies, ROVs, AUVs, and manned submersibles).

3.1.1 Test Set-up

The two types of oil (No. 6 fuel and Sundex) and asphalt from the first test were used again, as well as a new slurry oil with a high enough density so that addition of barite was not required. During the tests, the water temperature was about -1° C and the salinity was 23 parts per thousand. Table 2 gives the densities (in grams per milliliter (g/ml)) and the estimated viscosities (in centipoise (cP)) for the oils used in Phase II.

Table 2. Phase II oil types and properties.

	No. 6 Fuel Oil	Sundex 8600	Tesoro Slurry
Density (g/ml @ 1°C)	1.083	1.071	1.0626
Viscosity (cP @ 30.5° F (-0.8°C))	700,000	550,000	80,000

3.1.2 Test Trays

A new test configuration was designed using ten trays, each 2.4 meters by 6.1 meters (8 ft by 20 ft), resulting in a 12 meters by 12 meters (40 ft by 40 ft) test area. The trays had 4-inch sides and were filled two to four inches with four types of bottom or substrate (stone chip/sand mix, river silt, pea gravel, and #100 sand). Each tray had a different combination of oil types, oil deposit configurations (approximately one inch deep), and substrates. Rocks and seaweed were placed intermittently. The layout and contents of the trays are shown in Figure 16. Figure 17 shows the details of the target configurations.

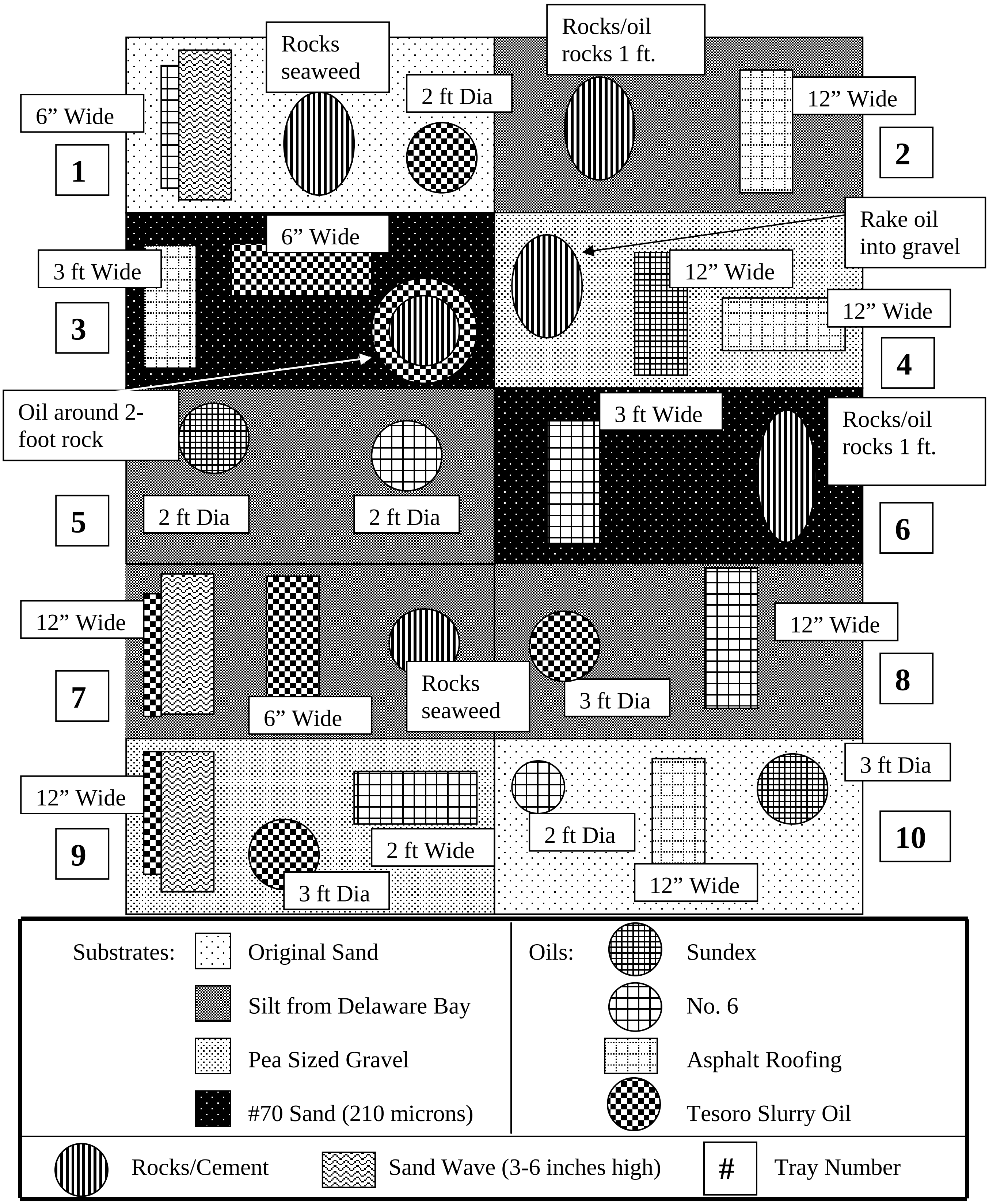


Figure 16. Phase II test tray configuration (not to scale).

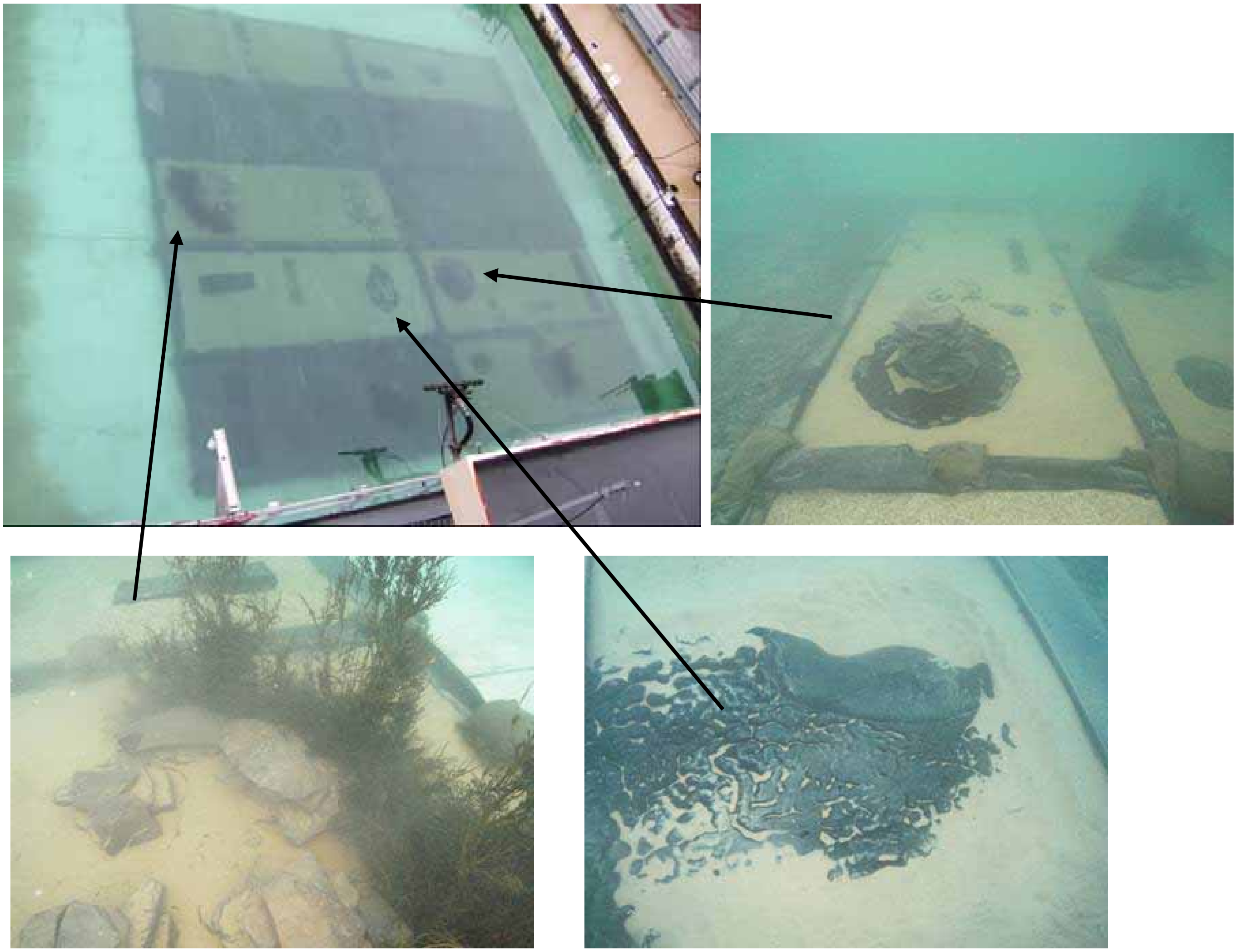


Figure 17. Details of tray configurations.

3.2 RESON, Inc. 7125 SeaBat Sonar System

3.2.1 SeaBat System Modifications

RESON modified their SeaBat system with an algorithm to interpret the data from their multi-beam echo sounder. For input, the detection algorithm uses calibrated backscatter levels from which the backscattering strength (BS) is derived. The detection algorithm functions in two steps. First, it estimates bottom topography and uses it to set a zero boundary. Then signals of BS below that boundary are evaluated graphically as “oil” to produce “bins.” The BS of the bins is then compared to a reference angular response curve for black oil. (The reference curve is based on measurements carried out in independent tests by RESON in 2008, also at the OHMSETT facility.) If the average difference between the reference and measured backscatter is below a pre-set threshold, the response is classified as oil.

Calibration of the system is crucial. The best method is to use a smooth hard (metal) sphere directly below the sonar. The correction factor calculated is then applied to all data. A calibration can also be done using a known type, such as in this case, the bottom of the tank.

The sonar was mounted on OHMSETT's moveable bridge and positioned approximately 1.9 m (6.2 ft) above the bottom of the test tank. The depth to the sediment of the trays was approximately 1.65 m (5.4 ft). The swath width applied was 110°, consequently the swath width on the ground was approximately 4.9 m (16.1 ft). Five survey passes were conducted to cover the test area with an overlap of approximately 2 m (6.6 ft). A sound velocity probe was mounted beside the sonar to provide sound velocities in real time to the beam former. The detection algorithm was set up in a software package, MATLAB, which is not embedded in the sonar software. A GPS device was installed above the sonar for real-time positioning data acquisition. Processing was done off-line and the input from the GPS units was correlated with the data.

3.2.2 SeaBat Results

Evaluation of the detections was based on the areas of the detected objects rather than on the number of detected objects. Evaluation based on number of detected objects would discriminate against the limited number of large detected areas in favor of the high number of small areas. The detection software estimated the area of each detected patch. For each detected patch, it was decided qualitatively whether a detected patch belonged to a real patch. For each survey, the detection rate and the false alarm rate were derived.

Figure 18 and Table 3 show the results for sonar position #3 (near the centerline of the array). The other four positions showed similar results. It appears that the software algorithm can learn what is most likely oil versus bottom and automatically outline these areas (Figure 18(b)). This includes complex geometries with oil near rocks and seaweed. While it is relatively easy for the model to distinguish oil from the bottom, the probability of detection can be increased as more information is known about specific oils and their properties and entered into the model.

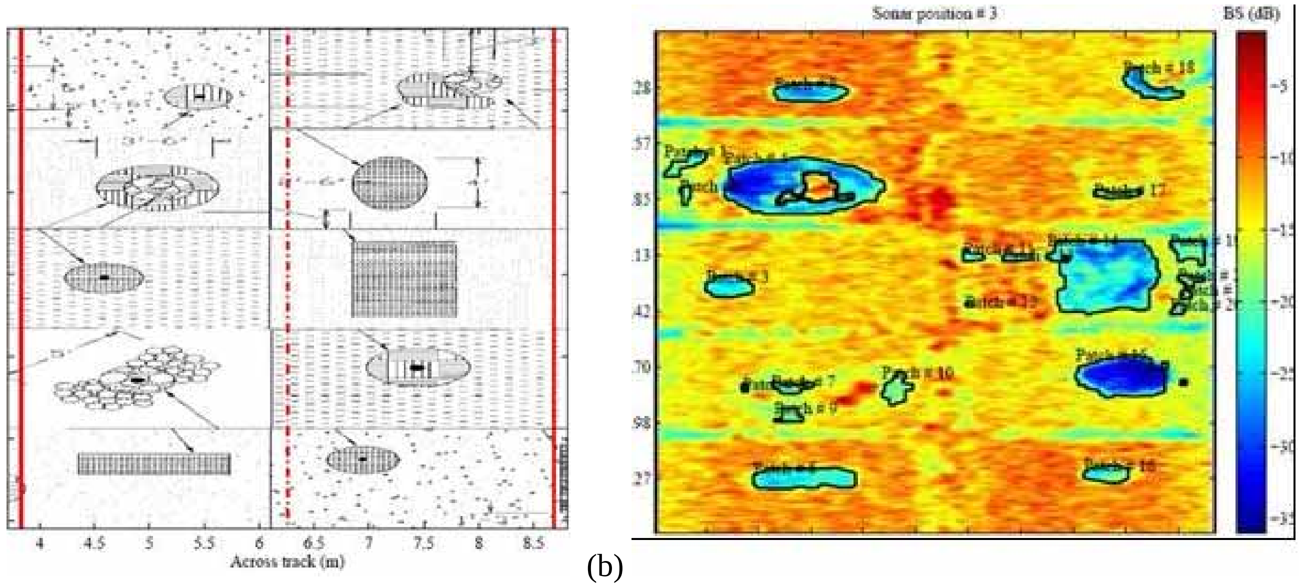
The five surveys yielded an average detection rate equal to 87 percent and an average false alarm rate equal to 24 percent. False alarms resulted from seaweed, fine sand, and small inaccuracies in the positions and dimensions of the objects in the trays.

Data processing was not done in real time but was done later on a separate computer. Because the rate of data acquisition outstripped the rate of data processing, the lag time to produce the results accumulated. It was estimated that the earliest processing results would lag real time by 8 minutes. Total processing time for one square mile is a function of depth (or sonar altitude), which impacts sweep width. Total processing time goes up exponentially as depth decreases. Total processing time would be 12 hours in 30 meters of water and increase to 22 hours in 10 meters of water. (These figures assume a ping rate of $15s^{-1}$ and a vessel speed of 6 knots.) While not done in real-time, the data transfer and calculations were completed for the entire test section in less than one day for the 400 kHz runs. Additional tests were done at 200 kHz. In an attempt to demonstrate coverage capability, a slow-ping run at 400 kHz that used 1 ping/second at a tow speed of 0.5 knots was conducted. This is equivalent to using 10 pings/second at 5 knots. The additional data are not included in this report but were used to estimate coverage capability.

RESON estimates that the detection processing time for a 1 square mile survey at a depth of 30 m can be made in 12 hours. At shallower depths the swath will be smaller, thus requiring more runs over the area. At deeper depths, the swath will cover a larger area, and the processing time for a 1 square mile survey will be reduced at the cost of poorer resolution. The detection processing software currently uses raw beam-formed signals as input. This has been done in order to ensure full control over all the stages of the computations. When the input signals are replaced by "snippet" data, which are the type of data that only originate from

the region near the seabed, the computation time is expected to decrease significantly. Lag time may also be decreased by increasing the number of data processors or computer speed.

There appear to be some discrepancies for left and right beams when observing the same targets because of the geometry differences. This may require additional overlaps when performing actual searches.



(a) (b)

Figure 18. RESON (a) layout of trays and (b) sample results. Dotted red line in (a) is instrument centerline.

Table 3. Detections and missing detections for RESON position #3.

Oil Patch	True area (m^2)	Patch No.	Estimated area (m^2)	Missing area (m^2)
T1C (Tesoro)	0.28	11	0.28	0.01
T2A (Tesoro)	0.37	23	0.24	0.13
T3C (Scattered oil)	0.07	1,2,3	0.4	-0.33
T3D (Tesoro)	0.86	5	1.29	-0.43
T4A (#6 Oil mixed into stone)	0.73	22	0.08	0.66
T5B (#6 Oil)	0.29	4	0.21	0.08
T6A (#6 Oil)	1.67	19	1.61	0.06
T8A (Tesoro)	0.66	20	0.76	-0.1
T9D (# 6 Oil)	0.93	7	0.46	0.47
T10A (# 6 Oil)	0.29	21	0.15	0.14
Total	**6.15**		**5.47**	**.68**

3.2.3 Other Considerations

3.2.3.1 Areal Coverage, Processing Time

There are trade-offs to consider for bottom coverage, speed of tow, and depth. To ensure some overlap of coverage of the bottom, the altitude of the transponder above the sea bed must be greater than 10 meters at a tow speed of 6 knots. Slower speeds or deeper water will increase the overlap of each ping. The amount of time needed to perform the processing is about double the data acquisition time at 100 meters but almost four times at 20 meters (see Figure 19). The requirement for surveying and processing for 1 square mile in

12 hours is met at a transponder altitude of 30 meters. The operators must understand the size of a patch of oil that is of interest (amount recoverable, amount that could be toxic to environment, etc.) and make decisions about the coverage, processing time, and resolution.

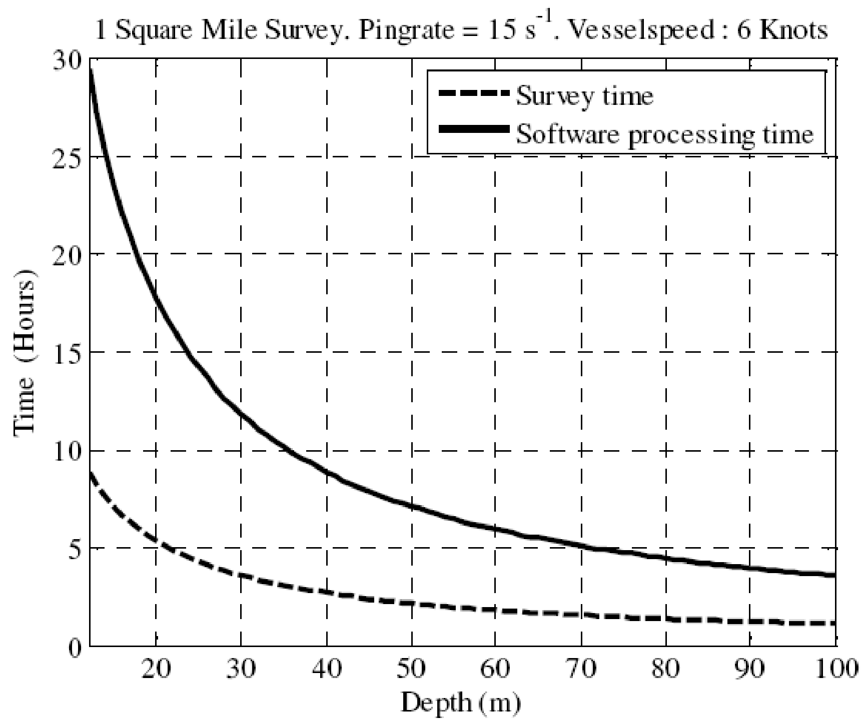


Figure 19. Estimated survey and processing time for a one square mile survey as a function of depth.

3.2.3.2 Summary

Methods are needed to reduce the processing time. Several options are available including reducing overlap or using a range-gate type of analysis to reduce the amount of data collected. Creation of a library of oil response characteristics and typical returns for various bottom types could enhance oil detection. Likewise additional "seaweed" detection algorithms could reduce false alarms. Data from the 200 kHz tests need to be analyzed to determine if this is useful in finding buried oil.

3.3 EIC Laboratories Fluorescence Polarization (FP)

3.3.1 EIC System Modifications

Based on the results of the Phase I development and testing, an autonomous, compact, underwater FP prototype instrument was designed and fabricated in Phase II. This instrument is about 20 inches (0.51 m) long and weighs about 16 pounds (Figure 20(a)). The altimeter sonar is the black rectangular piece attached on the outside of the cylinder. The FP instrument prototype was designed to be compact, remotely operated, and housed in a waterproof cylindrical housing so that it could be easily configured and deployed with different types of platforms such as towed bodies, ROVs, AUVs, and manned submersibles.

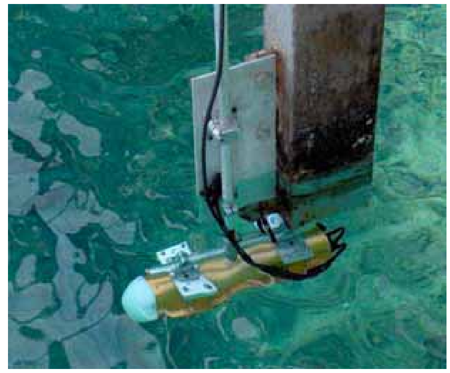
(a)  (b) 

Figure 20. EIC FP probe (a) close-up and (b) in the test tank at OHMSETT.

The main components of the probe are as described in Section 2.4.1 and did not change from Phase I. Detection of the two FP components is done with two fiber optically coupled photomultiplier tubes (PMT) incorporating bandpass filters (15 nm bandwidth) centered at 589 nm. Data acquisition is performed through the embedded computer via software developed by EIC. The software in the embedded computer allows the FP instrument to be controlled remotely or to perform the detection in an automated fashion, including GPS tagging of the data acquired. A remote computer aboard the survey vessel can be used to control the operation of the FP instrument via serial communication. Instrument functions such as data acquisition, data display with GPS coordinates, instrument parameter inputs, and data logging can be performed remotely. The remote software both records and displays the raw fluorescence signals from the two PMT channels and also calculates and displays the polarization values. In addition, the software allows a GPS signal to be recorded along with the FP signals to allow georeferencing of FP data. The software allows the operator to change the PMTs data acquisition time, balance the response of the two signals from the two emission legs of the FP probe, and obtain the bias of the two PMTs.

3.3.2 EIC Results

During testing of the FP probe in the test tank at OHMSETT, the FP instrument was attached to one end of a 6-foot long, 1-inch diameter aluminum extension rod (Figure 20(b)), which allowed positioning of the FP instrument at a given depth in the test tank. The extension rod was attached to a metal flange that bolted to the bottom of the bridge tow bar. A GPS unit was mounted at the above-water end of the extension rod.

Grid scans of the test trays containing the oil targets were performed. Grid scans were started at one corner of the test bed and ended at the opposite corner, so that the first line and last line ends at the edges of the test bed. The tow bridge was moved from north to south, and at the end of each line the probe was translated by a set distance. The tow speed was kept constant during each of the scans.

Although the individual scan lines were straight and parallel, the detection results were scattered because of the accuracy of the GPS readings (see Figure 21 for sample results). The readings were taken about 0.3 meters (1 foot) apart, but the accuracy of the GPS was about 1 meter. The scatter indicates that some of the track lines crossed when in reality they did not. The GPS direction of travel also indicated that the instrument doubled back when it did not.

The results indicate that the FP instrument is capable of accurately detecting heavy oil in real time. Each of the oil targets in the test platforms showed significant fluorescence polarization signals and could easily be distinguished from the FP signal of the surrounding background. Figure 22 shows the FP results stretched and superimposed on the complete tray layout. Some of the problems with plotting the location of the oil are GPS position errors, but the reasons for missing some of the targets are not known. It is probably a combination of the GPS movement and trying to stretch the data to match the overall size of the schematic of the tray layout.

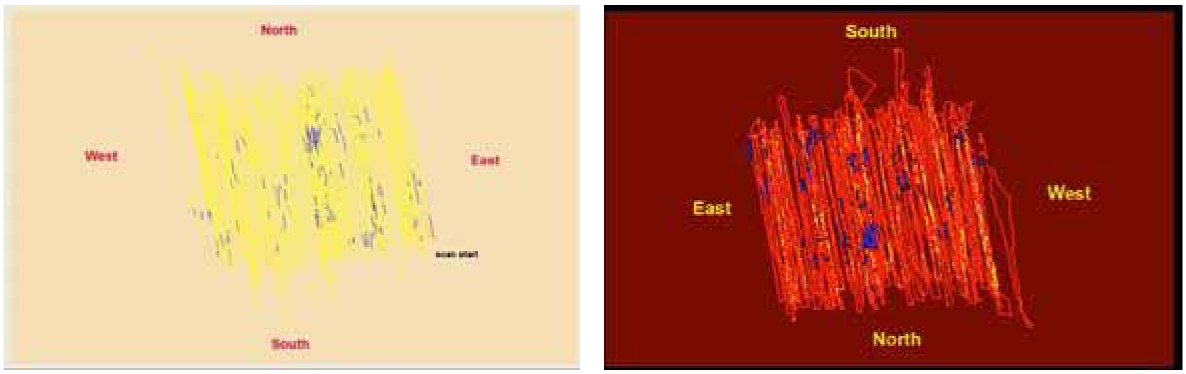


Figure 21. Two views of EIC FP sample results.

During the Phase II tests, bright sunlight, which did not occur during the Phase I testing, caused problems for the FP detection. Although some fluorescence was detected, sunlight saturated the input. It appears that there are several ways to reduce the external light. Solutions to minimizing the solar background interference such as spatial filtering and modulation detection schemes were investigated. The most promising is to modulate the laser and look for the returned fluorescence that will also be modulated.

Option 1, using a pinhole aperture to perform spatial filtering, could only reduce the background light by a factor of four, which is still not enough to minimize the solar effect. The other approach was to modulate the laser excitation at a specific frequency and set the detection for that frequency. When a unit so modified was evaluated in bright sunlight with Tesoro oil in a parking lot, the return fluorescent signal was also modulated (see Figure 23). The modulation technique still needs to be verified in an actual deployment

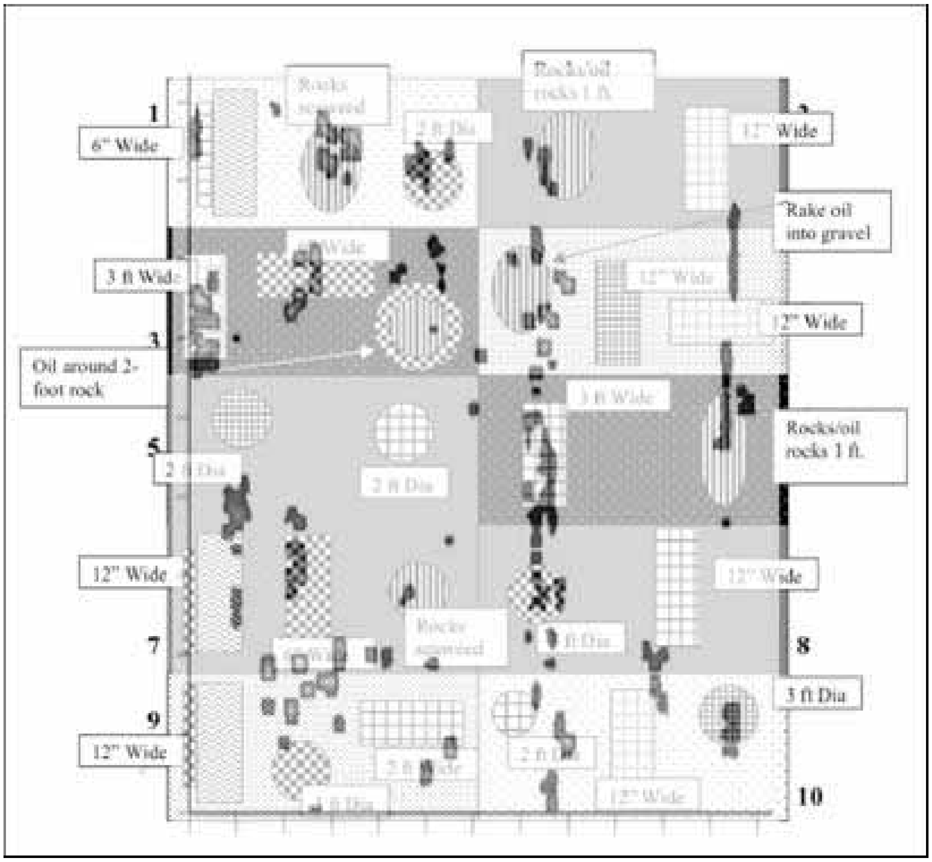


Figure 22. Superimposed images of tray set-up and FP results.

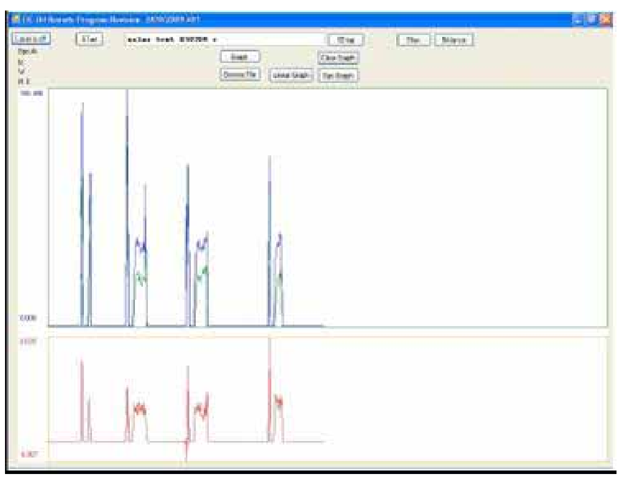


Figure 23. Results of modulation test conducted in bright sunlight showing output and return signals.

3.3.3 Other Considerations

The use of fluorescence polarization increases the usefulness of lasers over standard fluorescence. With the addition of the modulation process, the amount of false alarms is greatly reduced. The problem of turbidity may still limit the use of this system.

The areal coverage of a single sensor is limited. Indications are that several units could be mounted in an array, but the footprint would still be limited by the small footprint of each. 100 percent coverage will be virtually impossible. This system could probably not be used to find a small amount of oil. The user must consider tradeoffs between coverage and resolution.

3.4 Tests of Opportunity

Three detection vendors came to OHMSETT using their own funds in order to take advantage of the test setup before it was dismantled. The results are discussed below.

3.4.1 BioSonics

3.4.1.1 BioSonics Description

This company tested their DT-X Digital Scientific Echosounder (Figure 24), a unit equipped with two single beam transducers (200 kHZ and 420 kHZ) that is usually used to classify substrate (sub-bottom) or submerged vegetation. It has a very narrow, 6^{o} beam width and weighs about 20 pounds. It is normally connected to a GPS system but was not for this test.

Figure 24. BioSonics DT-X Digital Scientific Echosounder sensor.

Approximately 93 acoustic datasets were collected from the test site over a two-day period. These were primarily collected as linear transects across the test site, the same as the scan lines of the other systems. The transects were made at known locations and at measured speeds, providing the ability to estimate position based on the timing of the acoustic samples.

3.4.1.2 BioSonics Test Results

The system was successful in classifying the oil as a different kind of material in real-time (see

Figure 25 and Figure 26 for sample results of one pass along the length of the tray). It was also able to differentiate the four types of bottom material that were used. This differentiation was made possible by collecting sufficient data to develop an on-site reference library so that the same bottom material could be recognized and designated as not of interest during a search for oil. BioSonics estimates that when working with an unknown bottom, it would take approximately 30 minutes to characterize the bottom type(s), prior to beginning the search for the submerged oil.

3.4.1.3 Other Considerations

It is unlikely that the methods used here will reliably detect and discriminate small quantities of oil in association with vegetation and complex rock environments. Oil patches thicker than those tested (1-2 inches) would probably be easier to detect. Further, there is a need for additional development of the reference library to include collection and analysis of acoustic data from other oil samples, in larger quantities, to continue development of a reliable tool.

This technology is already being used in many different environments by natural resource managers to classify substrate and measure submerged vegetation. These capabilities were developed with extensive testing and ground-truth trials over time. Presumably the same approach could be used for submerged oil.

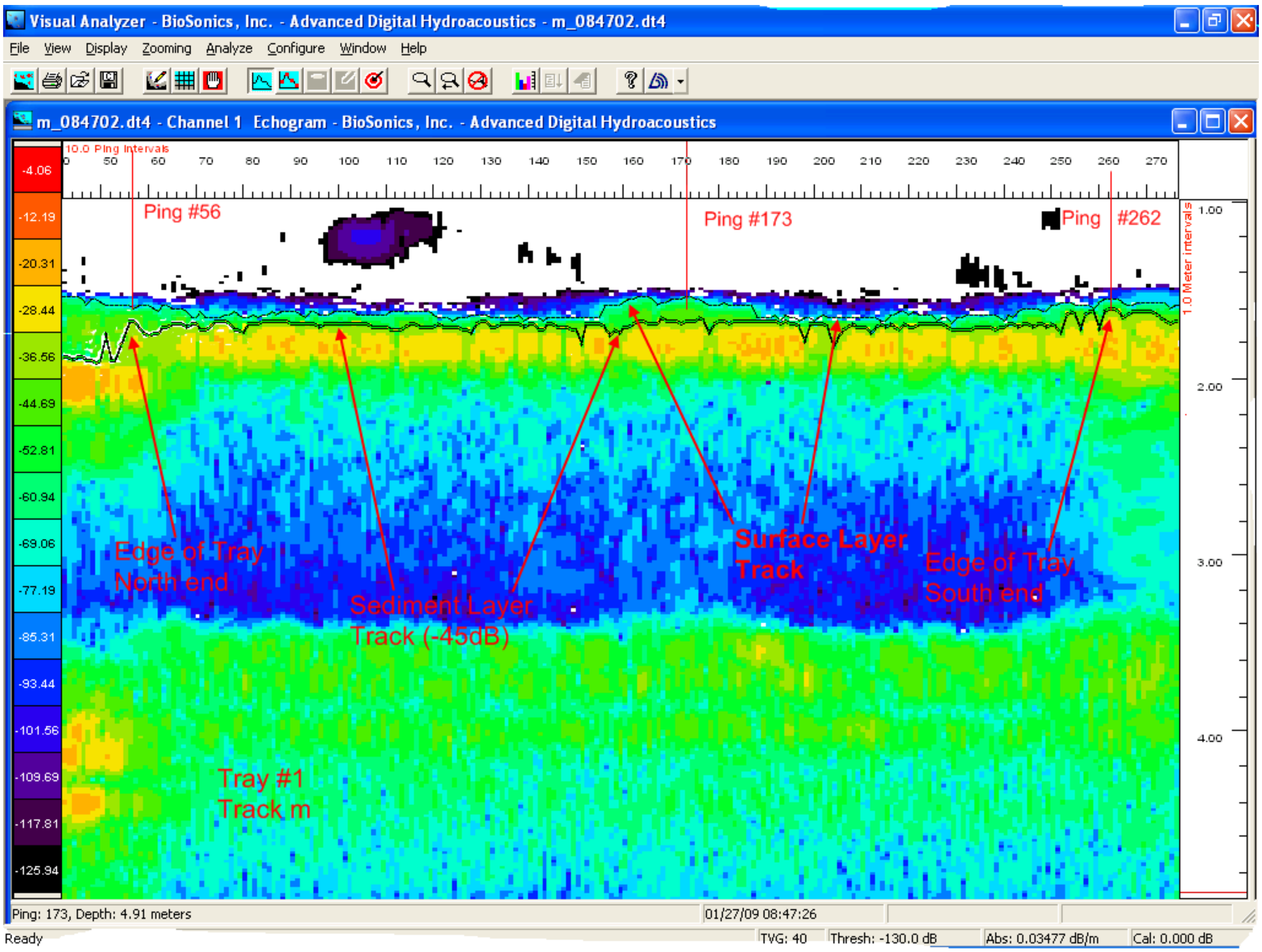


Figure 25. BioSonics sample echogram.

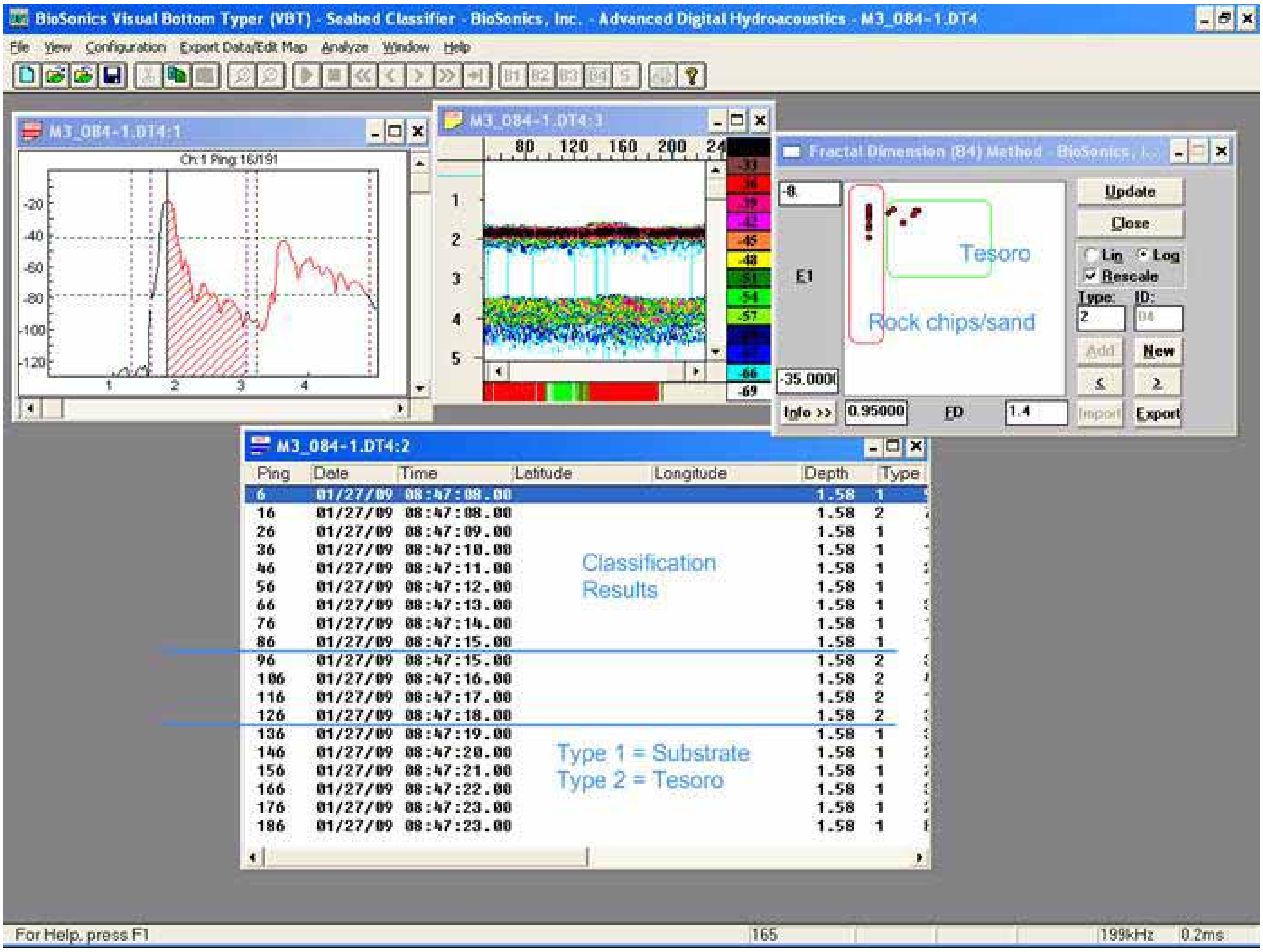


Figure 26. BioSonics sample analysis results.

3.4.2 CodaOctopus

3.4.2.1 CodaOctopus Description

The CodaOctopus EchoScope4D Imaging sonar, operating at 375 kHz, was used for these tests (Figure 27). This is the same system that the USCG is evaluating for other uses. It generates 128 by 128 beams in a 50 by 50 degree grid. It weighs about 45 pounds. The range of the sonar is from 1 meter to about 100 meters, depending on target strength (TS). The range resolution of the standard unit is 4 cm. It is typically deployed with a navigation system so that position and orientation are known. Like the RESON system, it uses return signal strength to differentiate between rocks, bottom, and oil.

Figure 27. CodaOctopus EchoScope 4D transponder.

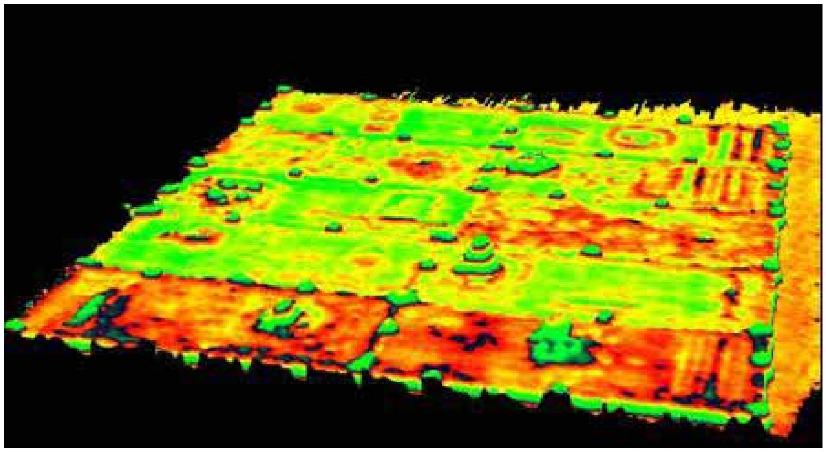
3.4.2.2 CodaOctopus Test Results

At almost all angles and frequencies, the contrast between oil and sand was about 15 dB. Sample results are shown in Figure 28: (a) shaded mosaic showing height (bathymetry); (b) raw data for area containing oil, rock, and seaweed; and (c) data after Underwater Inspection System (UIS) software processing. The company recommends that typical seabed types and heavy oil types be analyzed and their respective intensity returns (TS) measured as functions of frequency and angle of incidence. The TS database can then be used by a calibrated EchoScope to determine the class of seabed. A calibrated EchoScope used for this application will give calibrated TS data compensated for projector beam pattern.

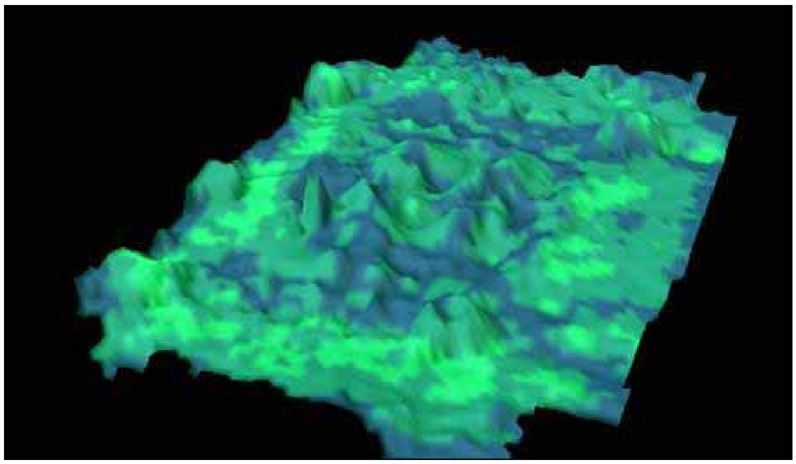
With online navigation included, an EchoScope survey will typically be carried out at 3 to 5 knots and therefore cover large areas efficiently. (This equates to 5 to 8 hours for complete coverage of 1 nautical mile by 1 nautical mile area at 100 meter swath width and 20 percent overlap.) Mosaics will be built on-the-fly using the UIS software. The UIS mosaic software uses averaging in geo-referenced cells – a technique that improves the signal-to-noise ratio significantly. As the data are instantaneous 3D, a vessel can move to an object of interest and obtain better data and even use it to position tools or divers in zero visibility water.

3.4.2.3 Other Considerations

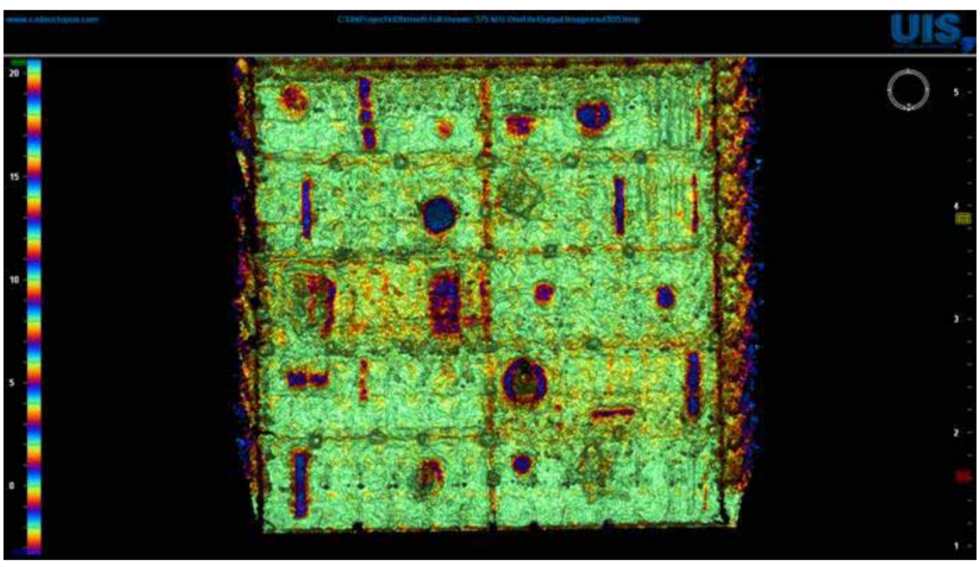
CodaOctopus recommends that a calibrated instrument be used in any further tests. This will compensate for combined receiver and projector sensitivity and result in fully normalized image intensity. The intensity of returns is the most important parameter in distinguishing between sand and oil. None of the fully calibrated echoscope heads were available at the time of the OHMSETT tests.



(a)



(b)



(c)

Figure 28. CodaOctopus sample results. (a) shaded mosaic showing bathymetry (color palette wraps around so red to red spans 20 cm elevation); (b) raw data of area containing oil, rock, and seaweed; and (c) data after UIS software processing (blue is oil).

3.4.3 SRI International

This company was funded by MMS to evaluate real-time mass spectrometry that has been used to map the field of a sewage outfall among other things. This system uses a different approach than the WHOI system. The cylindrical vessel is normally mounted in a remotely operated vehicle or autonomous vehicle. As seen through the windows of the OHMSETT tank (Figure 29), it was strapped into its maintenance stand for this use. No oil was detected in the tank but the system was later able to detect low-level components in a barrel in a high bay area at OHMSETT. This is similar to the experience that WHOI had with their system. SRI also indicated that the development of a pressurized system might allow the detection of heavier, less volatile compounds.

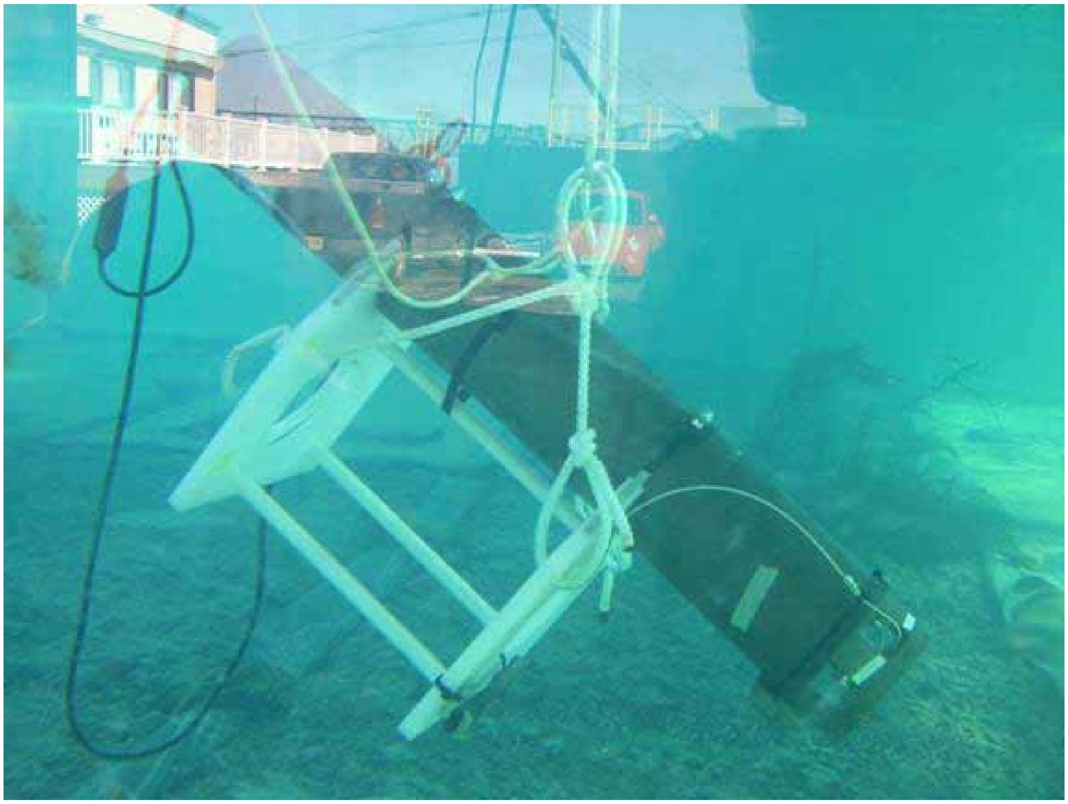


Figure 29. SRI International mass spectrometer.

3.5 Phase II Summary

3.5.1 Test Set-up Considerations

The test setup was as realistic as it could be given that the oil was contained. The bright backscatter did affect systems. The water was significantly cold (30-31 ^{o}F and under ice) but temperature did not seem to affect systems once they had warmed.

3.5.2 Prototype Test Results

Table 4 provides a summary of the prototype test results compared to the BAA performance requirements listed in Section 3.1.

Table 4. Phase II test results.

Requirement	RESON	EIC	BioSonics	CodaOctopus	SRI International
Identification of heavy oil on sea floor (80% certainty)	Yes	Yes	Yes with some limitations	Yes with additional work	No
Ability to detect oil on the sea floor from at least 1 meter away	Yes	Yes	yes	Yes	No
Real time data	No	Yes	Yes	Yes	Yes
Able to provide data for all sea floor conditions	Yes (some false alarms from seaweed; oil under gravel not detected)	Yes, although turbidity results in reduced instrument sensitivity	Yes	Yes	Yes
Search a one square mile area in a 12-hour shift	At depths over 100 ft	Yes, but limited coverage	Yes	Yes	Undetermined
Water currents of up to 1.5 knots	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this
Operate in up to 5 foot seas	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this	Yes, if mounted on boat/ROV that can handle this
Operable during the day and night	Yes	Strong solar background originally reduced performance, but modifications eliminated the problem.	Yes	Yes	Yes
Able to be set up within 6 hours	Yes	Yes	Yes	Yes	Yes
Easily deployable and transportable	Yes	Yes	Yes	Yes	Yes
Capable of being deployed from a vessel of opportunity and a variety of other platforms	Yes	Yes	Yes	Yes	Not clear

The evaluation of prototype systems was accomplished and several additional systems were tested. All systems need further development to make them into practical tools. In addition, the complexity of the environment was limited and the instruments should be evaluated further in the field.

In General:

- The methods were successful in detecting oil in a benign environment.
- There is no single method that can cover 100 percent of the area with no false alarms.
- Resolution of results is still and issue.
    - Easier if oil stays together.
    - Random hits need to be correlated.
- Use of techniques in turbid water and very soft bottom (such as rivers and harbors) is also an issue.
- Additional research needed for real-time mass spectrometry systems.

4 CONCLUSIONS

The technologies presented here represent an improvement over the existing ad-hoc methods. Although these systems have not been tested in the difficult harsh environments of low visibility, currents, and complex bottoms, they may be immediately useful in some situations, which could reduce the amount of effort and increase reliability of oil detection on the bottom or in the water column. Additional work needs to be done for all systems before they can be considered fully operational and it is hoped that the vendors can find additional funding sources.

The multi-beam and imaging sonars appear to be the best sensors to conduct wide area detection. Some of the signal return issues, which cause false positive detections for the low grazing angles of common side-scan sonar, are reduced in the systems tested. Most systems should be able to automatically detect large clumps of oil, but the resolution for widely dispersed product is still not complete. Spill responders should ensure that detection equipment has some type of processing software to interpret raw sensor data. This will ensure timely processing and require minimal training for response personnel. The sooner that a system is deployed before the oil breaks up, the better will be the chance that detection will occur.

The laser systems and smaller beam sonars may be better suited as a follow-up to the wide scan areas. These should provide better resolution and should be able to calculate general thickness which could provide some information about the amount of oil. The narrow areas covered could introduce resolution issues especially for widely scattered oil. On the other hand, the narrow area covered could be advantageous for guiding recovery efforts.

The real-time mass spectrometry systems should be evaluated for neutrally buoyant oil detection in the water column. For some spills, especially those in rough waves or fast moving currents, these instruments may be useful in tracking plumes. This would be especially useful for municipalities and power plants that use the water for cooling.

Positioning of the systems should be evaluated according to needs. In good visibility, the oil can be located within 5-10 meters that will permit divers or other operators to find it for recovery. For limited visibility and under special circumstances, underwater navigation systems, similar to the WHOI system, should be utilized for better accuracy.

5 RECOMMENDATION

The companies that had systems evaluated here and other related technologies should be encouraged to further develop the systems. Regulations require that vessel and facility plans contain response techniques and that the response organization has the equipment to respond to submerged oils. As progress is made on their development, regulations should also ensure that this capability is available for heavy oils (Type V) and those that could sink if exposed to the environment. Research funded by the Coastal Response Research Center (CRRC) at the University of New Hampshire is being done in Canada to further document what conditions are needed to cause oil to sink. These research results should provide responders with better information about oil behavior. Better models for submerged oil should also be developed that can be used to predict behavior and help further define detection and recovery techniques.

The use of this equipment by a Federal On-scene Coordinator (FOSC) is limited at this time due to the level of development. Guidance is contained in the Appendixes that provide information about the specific technologies tested. A decision-tool and recommendations for FOSC use is contained in Appendix E.

These types of systems should be integrated into recovery systems along with visual detection methods for clearer water. The USCG RDC has begun a project to develop full recovery systems that should be completed by 2012. It is hoped that companies that are in the field of detection will combine with other hardware manufacturers to develop systems that can be:

- Easily deployed in response to sinking oil.
- Be readily available, either through taking off the shelf or having a clear plan of integration.
- Be able to clearly find the oil and immediately recover it before it has a chance of being disturbed.

6 REFERENCES

Barbini, R. F., Colao, R. Fantoni, C. Ferrante, A. Palucci and S. Ribezzo. (2000). "Development of LIDAR Fluorosensor Payload for Submarine Operation," in *Proceedings of EARSeL-SIG Workshop LIDAR*, Dresden, FRG, pages 39-45, June 2000.

Bello, J.M. (2009). "Fluorescence Polarization Detection of Heavy Oil on the Sea Floor – OHMSETT Testing Results Conducted on 1/19/2009 to 1/21/2009," EIC Laboratories, Inc., submitted to USCG R&DC, February 19, 2009.

Bello, J.M. & Clauson, S. (2008). "Fluorescence Polarization Detection of Heavy Oil on the Sea Floor – OHMSETT Testing Results," EIC Laboratories, Inc., submitted to USCG R&DC, January 2, 2008.

BioSonics, Inc. (2009). "BioSonics Report on OHMSETT Test Opportunity; Dates 1/26/2009 and 1/27/2009," submitted to USCG R&DC, February, 2009.

Brown, C. E., Fingas, M. F., Gamble, R. L. & Mysliski, G. E. (2002). "The Remote Detection of Submerged Oil", 3*rd R&D Forum on High Density Oil Spill Response*, March 11-13, 2002.

Brown, C.E., Fingas, M.F. & Marois, R. (2006). "Oil Spill Remote Sensing: Flights Around Vancouver Island", in *Proceedings of the Twenty-ninth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 921-929, 2006

Brown, C.E., Fingas, M.F., & Marois, R. (2004). "Oil Spill Remote Sensing: Laser Fluorosensor Demonstration Flights off the East Coast of Canada", in *Proceedings of the Twenty-Seventh Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 317-334, 2004.

Cabioc'h, F. (2002). "Sunken Hydrocarbons and Chemical Products: Possible Responses and Available Methods", *3rd R&D Forum on High Density Oil Spill Response*, Brest, France, March 11-13, 2002.

Camilli, R. & Bingham, B. (2008). "Detection of Heavy Oil on the Seafloor – Phase I Final Report," Woods Hole Oceanographic Istitution, submitted to USCG R&DC, March 11, 2008.

Castle, R.W., Wehrenberg, F., Bartlett, J. &. Nuckols, J. (1995). "Heavy Oil Spills: Out of Sight, Out of Mind", *1995 International Oil Spill Conference*, pages 565-571, 1995.

Coastal Response Research Center (CRRC). (2007). "Submerged Oil – State of the Practice and Research Needs," Durham, NH, July, 2007.

CodaOctopus R&D. (2009). " EchoScope Trials at OHMSETT January 28-29, 2009." Submitted to USCG R&D Center, February 9, 2009.

Committee on Marine Transportation of Heavy Oils, National Research Council. (1999). "Spills of Nonfloating Oils: Risk and Response," National Academy of Sciences, 1999.

Elliott, J. (2005). "An Analysis of Underwater Oil Recovery Techniques, *2005 International Oil Spill Conference*, 11 pages, 2005.

Eriksen, M.T. (2009). "Prototype Demonstration Report – HSCG32-07-C-R00030, Deliverable 11," RESON, Inc., submitted to USCG R&DC, May 21, 2009.

Eriksen, M.T. & Maillard, E. (2007). "Proof of Concept Demonstration Report – HSCG32-07-C-R00030, Deliverable 5," RESON, Inc., submitted to USCG R&DC, December 21, 2007.

Fant, J.W. & Hansen, K.A. (2005). "U.S. Coast Guard Oil Spill Remote Sensing: Preliminary Laser Fluorosensor Studies", in *Proceedings of the Twenty-eighth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 861-872, 2005.

Fant, J.W. & Hansen, K.A. (2006). "U.S. Coast Guard Laser Fluorosensor Testing", in *Proceedings of the Twenty-ninth Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 951-964, 2006.

Hansen, K.A. (2009). "Research Efforts for Detection and Recovery of Submerged Oils," in *Proceedings of the Thirty-second Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, 2009 (in preparation).

Hansen, K.A, Bello, J., Clauson, S., Eriksen, M.T., Maillard, E., Camilli, R., Bingham, B., Morris, J. & Luey, P.J. (2008). "Preliminary Results for Oil on the Bottom Detection Technologies," in *Proceedings of the Thirty-first Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, 2008.

Michel, J. (2006). "Assessment and Recovery of Submerged Oil: current State Analysis," prepared for US Coast Guard Research and Development Center, June, 2006.

Michel, J. & Galt, J.A. (1995). "Conditions Under Which Floating Slicks Can Sink in Marine Settings," *1995 International Oil Spill Conference*, API Publication No. 4620, American Petroleum Institute, Washington, D.C., pp 573-576, 1995.

Morris, J. & Luey, P.J. (2008). "Modification and Use of the Laser Line Scan System as an Optical Tool for the Detection of Heavy Oil on the Seafloor – Proof of Concept Demonstration Report," Science Applications International Corporation, submitted to USCG R&DC, February 1, 2008.

Parthiot, F., De Nanteuil, E., Merlin, F., Zerr, B., Guedes, Y., Lurtin, X., Augustin J.M., Cervenka, P., Marchal, J., Sessarego, J.P., & Hansen, R.K. (2004). "Sonar Detection and Monitoring of Sunken Heavy Fuel Oil on the Seafloor," *Proceedings of the Interspill 2004 Conference*, Trondheim, Norway, June 14-17, 2004.

Parthiot, F. (2002). "Monitoring of Sunken Fuel Oils," *3rd R&D Forum on High Density Oil Spill Response*, March 11-13, 2002.

Schnitz, P. R. & Wolf, M. A. (2001). "Nonfloating Oil Spill Response Planning," *2001 International Oil Spill Conference*, pp 1307-1311, 2001.

Short, R.T. (2009). “Demonstration of Detection and Location of Submerged Oil Using In Situ Mass Spectrometry,” SRI International, submitted to USCG R&DC, February, 2009.

Usher, D. (2008). “The Use of Manned Submersible Units to Accomplish Submerged Oil Recovery,” *International Oil Spill Conference*, Savannah, GA, May, 2008, pages 1289-1291.

Wendelboe, G., Fonseca, L., Eriksen, M., Hvidbak, F., and Mutschler, M. (2009). “Detection of Heavy Oil on the Seabed by Application of a 400 kHz Multi-beam Echo Sounder,” in *Proceedings of the Thirty-second Arctic Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, ON, 2009 (in preparation).

(This page intentionally left blank.)

APPENDIX A. OHMSETT TEST FACILITY

The Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT), now called The National Oil Spill Response Test Tank Facility (www.ohmsett.com), is the only facility where full-scale oil spill response equipment testing, research, and training can be conducted in a marine environment with oil under controlled environmental conditions (i.e., waves, temperature, oil types). The facility provides an environmentally safe place to conduct objective testing and to develop devices and techniques for the control of oil and hazardous material spills. OHMSETT's mission is to increase oil spill response capability through independent and objective performance testing of equipment, providing realistic training to response personnel, and improving technologies through research and development.

OHMSETT is located at the Naval Weapons Station Earle Waterfront in Leonardo, New Jersey (approximately one hour south of New York City). It is maintained and operated by the Department of Interior Minerals Management Service (MMS) through a contract with MAR, Incorporated of Rockville, Maryland. OHMSETT's above ground concrete test tank is one of the largest of its kind, measuring 203 m long by 20 m wide by 3.4 m deep. The tank is filled with 2.6 million gallons of crystal clear saltwater.

OHMSETT has a mechanically operated control bridge that spans the width of the tank and traverses the tank's length; two stand-alone work bridges can be stationary or rigidly attached to the mobile control bridge. The OHMSETT test tank allows testing of full-scale equipment. The tank's wave generator creates realistic sea environments, while state-of-the-art data collection and video systems record test results. The facility has proven to be ideal for testing equipment, evaluating acquisition options, and validating research findings.

Public and private sector entities are invited to contract the use of OHMSETT as a research center to test oil spill containment/clean-up equipment and techniques, to test new designs in response equipment, and to conduct training with actual oil spill response technologies.

Features & Capabilities

- A main towing bridge capable of towing test equipment at speeds up to 6.5 knots
- An auxiliary bridge oil recovery system to quantify skimmer recovery rates
- A wave generator capable of simulating regular waves up to one meter in height, as well as a simulated harbor chop
- A movable, wave-damping artificial beach
- An oil distribution and recovery system that can handle heavy, viscous oils and emulsions
- A control tower with a fully-computerized 32-channel data collection system as well as above-and below-water video
- A centrifuge system to recover and recycle test oil
- Blending tanks with a water and oil distribution system to produce custom oil/water emulsions for testing
- A filtration and oil/water separator system
- An electrolytic chlorinator to control biological activity
- Permanent and mobile storage tanks that can hold over 227,000 liters of test fluids
- A vacuum bridge to clean the bottom of the tank
- Staging and shop area for special fabrication

(This page intentionally left blank.)

APPENDIX B. ACOUSTIC DETECTION OF HEAVY OIL

Acoustic techniques for sea floor mapping are widespread and they could potentially provide relatively rapid coverage for heavy oil detection. Side-scan sonar mapping systems are normally interfaced with a Global Positioning System (GPS) and hydrographic mapping software to generate maps of seafloor features. These systems can provide relatively rapid coverage, and are primarily useful for identifying areas of natural collection for the sunken oil. Multi-beam sonar systems can potentially be used to differentiate the oil from the sea bottom by sensing the contrast in roughness.

B.1 Acoustic Detection Mechanism

Sonar mapping techniques rely on acoustic sounding principles, specifically on the differential density and sound speeds of water compared to those of sediments and the seafloor. Oil and oil-sediment mixtures will differ from sediments in a similar manner and thus should be recognizable.

A sonar device contains a transducer that converts the electrical signal from a transmitter within the transducer into an acoustic pulse, and transmits that energy into the water. In reciprocal fashion, the transducer receives acoustic echoes (from targets on the bottom) and converts them to electrical signals. The pulse of energy travels through the water at a speed of approximately 1500 m/sec, and depends on pressure (therefore depth), temperature (a change of 1 °C ~ 4 m/s), and salinity (a change of 1% ~ 1 m/s). When the acoustic pulse encounters an object, some of the energy (i.e. an echo) is reflected back to the transducer (this reflected energy is also called backscatter (see Figure B-1)) and some continues forward.

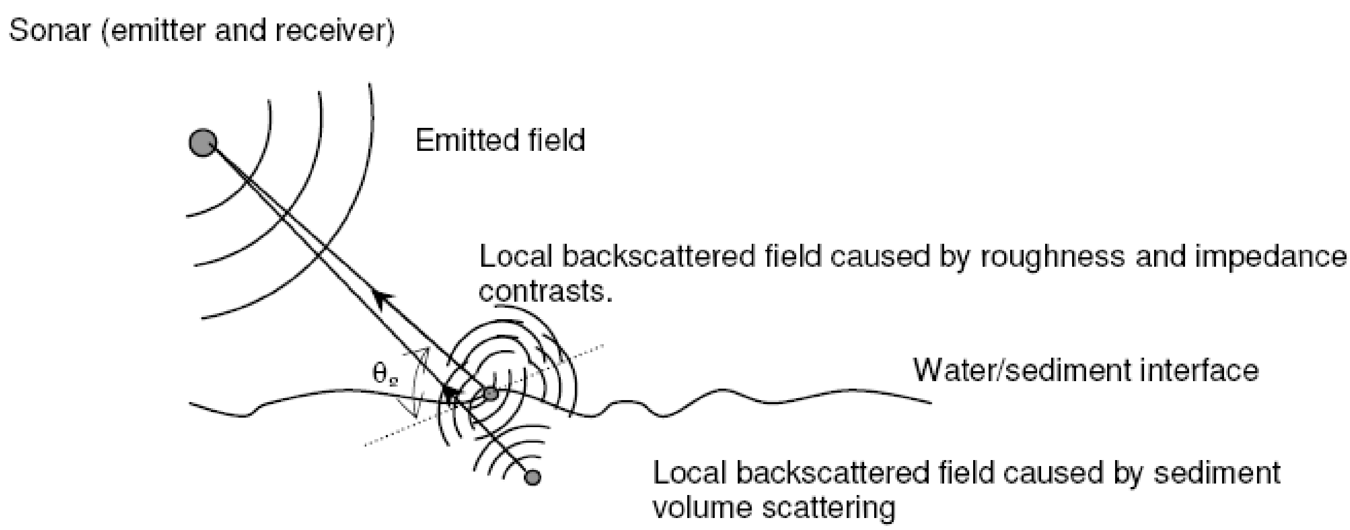


Figure B-1. Acoustic backscattering from the sea floor.

The amount of energy that is forward versus backscattered from the seabed is a result of impedance changes at the water/sediment interface, the roughness of the water/sediment interface, and the sediment volume heterogeneities. These heterogeneities include objects buried in the sediment that reflect energy that is originally forward scattered rather than backscattered. The acoustic impedance of a material depends on its density, viscosity, and the speed of sound in the material. Impedance contrast and roughness governs the scattering mechanisms at the water/sediment interface. Sediment heterogeneities govern the scattering

mechanisms within the sediment volume. The intensity of the backscattered signal also depends on the acoustic frequency, and on the grazing angle θ_g (with respect to the seabed plane) of the incoming field. The return echo signal also depends on the equipment parameters (i.e. frequency, transducer's beamwidth, and others).

B.2 Data Processing

In order for a sonar system to serve as an oil detection tool, the data received from the sonar must be processed and interpreted. There are different types of processing used, usually based on the specific sonar equipment and target strength differences between the oil and the bottom. Vendors generally design software specifically to work with their systems.

Returns come in and an image is generated based on user-defined thresholds. That image then undergoes image processing to determine what is oil and what is not. If the signal level exceeds a user-selected threshold level, a mark appears on the echogram. The distance from the centerline to the mark is proportional to the travel time for the pulse to travel from the transducer to the target and back. Since the velocity of sound in water is known, range (distance from the transducer) can be calculated from this travel time. By collecting the echoes from many consecutive transmissions, the time in the acoustic beam, the change in range and the direction of travel of targets can be determined.

B.3 Advantages

There are some advantages to using an acoustic seafloor classification system. Appropriate systems are commonly available at relatively low cost. They are portable, so they can be deployed on boats of opportunity, and they have minimal power requirements. Due to their ping rates, they are also capable of collecting data quickly.

Multi-beam sonars can be designed to operate at different frequencies. Higher frequencies give better angular resolution. Lower frequencies provide lower resolution but offer additional range.

One advantage is that these systems are relatively common and thus their properties and peculiarities are well known.

B.4 Limitations

Sonar images need to be interpreted. Since oil spills do not occur frequently, vendors have not designed specific software to provide rapid delineation of oil patches on the bottom. Analysis has taken more than a day to identify oil on the bottom and this usually has to be confirmed. This is also usually complicated by biological interference (plants (particularly kelp) and animals) that can confound the signals. This time delay is not useful for many spills when the oil is still on the move.

Someone trained to interpret the image can generally do so rapidly. A couple of sediment samples, which could be taken during the survey, should be enough to allow accurate interpretation of the sonar data. They could also be augmented with video or imagery collection. The building of a library of oil-on-sediment returns would probably allow for more rapid interpretation. Again, this would require someone trained in oil recognition.

Systems with narrow swath width make continuous coverage of the seafloor difficult, and their acoustic "footprint" is relatively small and dependent on depth. These types of systems would be useful for confirming the presence of oil once its general location is suspected.

Some sonar systems may be unable to distinguish between oiled sediments and underlying sediments because of their acoustic similarity. This is especially true in rivers and harbors. Therefore, sampling or in situ observations are necessary to confirm the maps. Because the sonar is reflecting the roughness or smoothness of the seafloor, oil that is covered by sediments may be missed in a sonar survey. Changes in salinity of the water will have a direct effect on the propagation of the Sonar's acoustic signal in the water.

(This page intentionally left blank.)

APPENDIX C. OPTICAL/FLUORESCENT DETECTION OF HEAVY OIL

Visual observations (by aircraft, ship, diver, or camera/television) have been the principal methods of locating and tracking submerged oil. Airborne photography and visual-based systems, which are widely available and can rapidly survey large areas, are frequently used to locate submerged oil. The performance of these systems is limited by water clarity and depth, the quantity of oil, and the characteristics of bottom sediment. Figure C-1 shows the transmission distance for the visible spectrum for various water types. Given the possibility of misidentifying natural materials (seaweed, seagrass beds) as oil, *in situ* observations are always required to validate airborne assessments. Direct observations can also be performed by divers within safe depth restrictions and visibility limits. Observations by underwater cameras, either operated by divers or deployed from ships, can also be used to locate submerged oil. These visual methods must generally be confirmed by sampling and have relatively limited coverage. During R&D Research, Hansen and Fant (2006) detected fluorescence from a target about 40 ft away in clear water using an airborne laser.

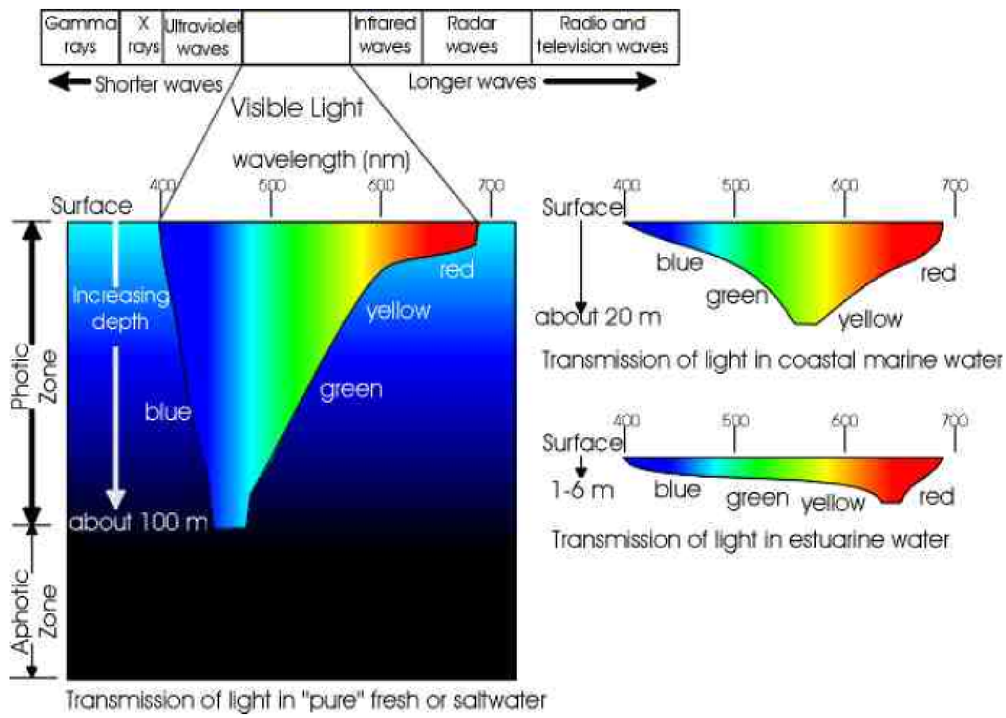


Figure C-1. Graphical representation of light transmission in water. Water color, turbidity, and other factors impact the actual attenuation of transmitted light, as well as any corresponding reflectance or fluorescence.

C.1 Laser Fluorescence Mechanism

An alternative detection technique using the visible light spectrum is fluorescence spectroscopy. Laser fluorosensors are active sensors that rely on the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is removed by the process of fluorescence emission, primarily in the visible region of the spectrum.

Crude and refined oil products are primarily composed of saturated and aromatic hydrocarbons, resins, and asphaltenes. Polyaromatic hydrocarbons (PAHs) are chemical compounds comprised of fused rings containing strong unsaturated bonds. Due to the structural arrangement of PAHs, they tend to fluoresce in response to light energy. Through the process of fluorescence, the light energy that was absorbed by the oil-based compound is released back to the ambient environment, returning the molecules to their original ground state. Despite a difference in molecular structure, alkanes (saturated hydrocarbons) will also fluoresce when exposed to a focused light source.

Various intensities and wavelengths of light can be used to excite PAH and alkane molecules into a state of fluorescence. However, numerous studies have shown that high-energy ultraviolet (UV) light in the wavelength range 200 nm to 400 nm is the most effective source of excitation, yielding the strongest fluorescent emission. PAH compounds responding to UV tend to fluoresce quite distinctly, emitting photons in the visible light wavelength range (400–600 nm: violet to orange), with specific wavelengths of emission serving to identify the types of PAH compounds present. Similarly, alkane molecules will fluoresce in response to UV, but they do so at a lower wavelength outside the visible light spectrum (UV-A bandwidth; 320-400 nm), making them less viable indicators of oil.

C.2 Fluorescence Polarization

In addition to oils there are other potential fluorophors (compounds that fluoresce) in the marine environment, such as chlorophyll from algae and seaweed. One technique developed to distinguish between oil and other fluorophors is fluorescence polarization (FP). FP measurements are based on the assessment of the rotational motions of species. FP can be considered a competition between the molecular motion and the lifetime of fluorophors in solution. If linear polarized light is used to excite an ensemble of fluorophors, only those fluorophors aligned with the plane of polarization will be excited. The FP depends on the fluorescence lifetime and the rotational correlation time (θ). The rotational correlation time is given by $\theta = \eta V/kT$, where k is the Boltzman constant, T is the absolute temperature, η is the viscosity, and V is the molecular volume. Thus, for viscous compounds, fluorescence polarization will be observed. Other fluorophors in the marine environment will not exhibit fluorescence polarization since they are a less viscous medium and will not be conducive to fluorescence polarization.

C.3 Advantages

Fluorescence based methods have several advantages, including they are non-contact (e.g., can be deployed with fiber optic probes for remote sensing), have high sensitivity to the presence of aromatic hydrocarbons, and can be easily miniaturized.

Fluorescence polarization (FP) enhances the selectivity of fluorescence by incorporating polarization into the measurement technique. FP measurements are based on the assessment of the rotational motions of species. In particular heavy oils, which are very viscous, will show significant fluorescence polarization when excited with polarized light.

C.4 Limitations

In addition to naturally occurring fluorescence that can interfere with fluorescence based methods, ambient or reflected light can affect results. For example during dockside tests of SAIC's Laser Line Scan System (LLSS), white test rays and white writing on polyethylene bags were visible as well as the oil. In the LLSS OHMSETT tests, the paint of the tank reflected the laser light. It is not known whether elements in the natural environment would also cause the same problem, but one would expect that a highly reflective clean sand could result in similar reflection of the laser light. In addition, turbid water could have the opposite effect by interrupting the signal such that oil cannot be detected.

(This page intentionally left blank.)

APPENDIX D. CHEMICAL DETECTION AND IDENTIFICATION OF HEAVY OIL

Direct sampling of the water column or seabed may be used to locate and map the movement of oil. Sampling can be done by a vessel, a remote vehicle, or a diver (in shallow water). Sampling generally becomes more difficult and time consuming as the water depth, current speed, and wave height increase. A variety of sampling techniques are available, including grab sampling of water or sediments with subsequent visual or chemical analysis, sorbent materials deployed on weighted lines or in traps, and core sampling of the seabed sediments. Sampling is typically limited in scope and may not provide representative observations of the impact area. Water-column and bottom trawls may be useful for selected spills because they can cover larger areas. The effectiveness of sampling methods is strongly dependent on the composition of the oil and oiled sediment and on environmental factors, such as current speed, water depth, and substrate type.

Some companies have developed instruments designed to conduct in situ sampling and analysis of the water column. These instruments perform a chemical analysis of the water to determine the presence of oil and identify its components. In situ chemical analysis techniques include mass spectroscopy and ultraviolet fluorometry.

D.1 Mass Spectroscopy

Mass spectrometry (MS) is an analytical technique that is used to identify unknown compounds, to quantify known compounds, and to determine the structure and chemical properties of molecules. It does this by ionizing the components to generate charged molecules and molecule fragments, and then measuring their mass-to-charge ratio (m/z). In an MS procedure, a sample is introduced into the MS instrument and its components undergo ionization through one of a variety of mechanisms (e.g., by impacting them with an electron beam), resulting in the formation of charged particles (ions). The m/z of the particles can then be calculated based on behavior of the ions as they pass through electric and magnetic fields generated by the MS instrument.

D.2 Ultraviolet Fluorometry

Ultraviolet (UV) fluorometry employs a flow-through, fixed-wavelength UV fluorometer to measure and map components of oil that can be induced to fluoresce. These are generally aromatic hydrocarbons. In situ and towed fluorometric detection devices are widely available and routinely used to detect and map petroleum leaks and spills. These systems may be mounted on buoys, boats, or remotely operated vehicles. When mounted on boats and coordinated with GPS, they can provide maps of the subsurface oil concentration field. They are restricted to making oil concentration measurements in the water column and have a detection range from parts per billion to parts per million, depending on environmental conditions and oil type. Given the three-dimensional nature of submerged oil plumes, mapping of subsurface oil requires an extensive effort.

D.3 Advantages

Mass spectrometers and UV fluorometers are able to detect wide range of components and distinguish between different chemical species. They are also able to provide real-time data.

D.4 Limitations

Detection and characterization of oil in the water column depends on the solubility of the oil in sea water. It is not clear whether oil that has been submerged for more than 1-2 days will emit volatile compounds and create a signature trail. It also means that the sensor may have to be very close to the bottom and be tightly controlled which will limit the speed of the sensor through the water. Bottom type and organic growth may further restrict the applicability of these systems.

APPENDIX E. RECOMMENDATIONS FOR FEDERAL ON-SCENE COORDINATORS FOR OIL SUSPECTED TO BE ON THE SEA BOTTOM

In responding to any oil spill, it is essential that the Federal On-scene Coordinator (FOSC) knows the location, area coverage, and general physical condition of the oil to effectively deploy cleanup resources and protect environmentally sensitive areas. Detecting and tracking oil beneath the surface is a particularly challenging problem. For the purpose of this report and following Coastal Response Research Center (2007), "submerged oil" describes any oil that is not floating at or near the surface. "Sunken oil" describes the accumulation of bulk oil on the seafloor.

E.1 Fate of Spilled Oil and Oil-based Compounds

When oils are initially released into the marine or aquatic environment, a number of processes can affect the slick. These include spreading, evaporation and oxidation, dispersion, dissolution, emulsification, biodegradation, and sedimentation. Chemical make-up, density, and viscosity of the oil will have a large impact on the resultant behavior of the spilled oil. Oil products with a specific gravity less than the surrounding seawater at the time of release will tend to form a surface slick, while oils with a specific gravity greater than that of the seawater will likely sink to the seafloor or suspend in the water column; under both conditions, the oil can be transported by currents. Deposits of sunken oil are challenging to detect, map, and recover following an oil spill. Methods of detection and mapping using existing techniques are often inefficient and time consuming, involve labor intensive searches, and thus contribute to low recovery volumes for these kinds of spills.

Oils and chemicals with similar physical properties and low solubility can make their way to the seabed through a number of different mechanisms:

- The pollutant has an initial specific gravity already greater than that of seawater.
- The specific gravity of the pollutant becomes greater than seawater through the incorporation of sediments either as a result of being stranded on sand shorelines and washed back into near-shore waters or becoming entrained with high levels of suspended sand in breaking waves (either on the beach or offshore bars).
- The oil sinks following a fire that not only consumes the lighter components but also results in heavier pyrogenic products as a consequence of the high temperatures associated with the fire.
- The pollutant is injected directly into the seabed and sticks to it through mechanical adhesion.

Since 1991, there have been at least nine major spills that involved submerged oil. All of the past spills where the oil submerged initially (without picking up sediment) were heavy, refined oil products or coal tar oil that were denser than the receiving water. Most of the past spills where the oil initially floated then sank were spills of heavy crude oils or heavy refined oil products that sank after picking up sand.

Regardless of whether the spilled oil exists as a surface slick or as a deposit at the sediment/water interface, natural physical processes within the water column (surface waves, tidal currents, etc.), evaporation, and dissolution will cause the spilled oil-product to weather and properties to change over time. Submerged oils however, weather at much slower rates than floating or stranded oil. Higher density oil deposits or tarballs on the seafloor are also affected by bottom current action and the incorporation of sediment grains into the

oil matrix. Exposure to near-bottom currents of significant magnitude may result in transport of the oil along the bottom by tidal, river, or storm wave currents and continued incorporation of native ambient sediment grains, as well as widespread dispersion from the original point of origin.

Submerged and sunken oil may move uncontrolled in the water column due to temperature changes, currents, gain or loss of sediments, and wave action. The result of a spill of heavy oil that sinks to the sea floor may therefore cause significant damage to the marine environment, recreational areas, sensitive industrial installations, and property such as boats and docks.

E.2 Tracking and Mapping Submerged Oil

The appropriate method for tracking and mapping a particular spill depends on whether the oil is suspended in the water column or deposited on the seabed and on the water depth and clarity. In general, visual and photobathymetric techniques are restricted to water depths of 20 m or less and are suitable for both suspended and deposited oil. Diver-based visual observations can only be used in low-current and small wave areas with moderately clear water. Acoustic techniques, video observations, water-column and bottom sampling, *in situ* detectors, and nets and trawls typically have no depth restrictions except that the water must be deep enough for the instrument to be deployed and operated safely. They become more difficult to operate, however, as the current speed and wave height increase. Measurements near the seabed become more challenging as the topographic relief of the bottom increases and the bottom surface becomes rougher. Fouling of instruments can be a serious issue.

Locating and identifying heavy oil are problems of growing concern as the use of heavy oil and related slurry products becomes more prevalent. Despite the technological improvements that have been made in identifying oils spills through surface slick detection, heavy oils with limited or no surface slick expression remain challenging. In recent years, a number of spills such as the M/T Athos 1 and DBL-152 (Michel 2006) have been difficult to remediate because of poor estimates of subsurface spill volume and the inability to track petroleum product migration (advection and dispersion on the seafloor and within the water column). This inability to provide clear estimates of subsurface spill extent and movement persists because of inadequate sensing technology. Experimental technologies such as airborne laser fluorescence show promise in detecting aromatic hydrocarbons at water depths to a couple of meters. However, the effectiveness of this technique rapidly deteriorates with increasing depth or water turbidity (Fant and Hansen 2006). Other methodologies such as side-scan sonar have been periodically employed but proven unreliable in detecting sunken oil (Michel 2006).

Present state-of-the-art techniques are generally slow, labor intensive, and expensive. Systems such as the Vessel-Submerged Oil Recovery System (V-SORS – an array of heavy chain and sorbent pom-poms dragged across the bottom) have proven effective in localizing the general areas of pooled and mobile spills, but are unable to determine precise locations or actual amounts of oil. Furthermore, because V-SORS and other technologies (such as sorbent drops and sediment cores) are used in contact with the seafloor, these systems pose significant risk to snagging on or otherwise damaging benthic marine life and structures (e.g., reefs, cables, and pipelines). Other non-contact seafloor survey techniques such as ROV video surveys pose the additional problems of only being operational in high visibility water and low sea states and generally being un-navigated, or if navigated, then requiring large and costly dynamically positioned ships. Table E-1 (modified from Michel (2006)) lists the advantages and disadvantages of a variety of submerged oil detection technologies and Figure E-1 shows a detection decision tree (Castle et al., 2005).

Table E-1. Advantages and disadvantages of submerged oil detection technologies (modified from Michel (2006)).

ADVANTAGES	DISADVANTAGES
Visual	
- Can cover large areas quickly using standard resources available at spills	- Only effective in areas with high water clarity - Sediment cover will prevent detection over time - Ground truthing required
Manual (V-SORS, Net Trawls, Snare Sentinels)	
- Could detect both pooled and mobile oil moving above the bottom - Relatively efficient in that large areas could surveyed - Provided spatial data on extent of submerged oil - Can vary the length of the trawl to refine spatial extent - Could be used in vessel traffic lanes - Good positioning capability with onboard GPS and navigation system	- Time and labor intensive for deployment, inspection, and replacement - Susceptible to snagging on the bottom - Cannot determine where along the trawl the oil occurred - Difficult to calibrate the effectiveness of oil recovery - Requires a vessel with a boom/pulley and adequate deck space on the stern for handling, inspection, and replacement - Requires use of white snare, which has to be special ordered
Side Scan Sonar	
- Good spatial coverage - Not affected by poor visibility - Good visualization of large oil accumulations and other bottom features (e.g., debris piles, pipelines)	- Once the oil spreads out, has reduced success at oil identification - Slow turnaround (days) for useful product - Needs validation of targets as oil - Less accuracy in muddy substrates
Multi-beam Sonar	
- Some systems can generate high-quality data with track lines - Good locational accuracy - Software detection algorithms can increase search efficiency	- Data processing can be slow - Requires extensive ground truthing - Requires skilled operators
Laser	
- Almost no false positives - Can use systems close to bottom - Data output easy to interpret	- Of limited use in turbid waters
Bottom Sampling	
- Can be effective in small areas for rapid definition of a known patch of oil - Low tech option - Has been proven effective for certain spills	- Samples a very small area, which may not be representative - Too slow to be effective over a large area - Does not indicate quantity of oil on bottom
Real-Time Mass Spectrometry	
- Able to detect wide range of components - Able to provide real-time data	- Droplets of oil or soluble oil must be in the water column - Oil on the bottom cannot be solid (as in low temperatures)

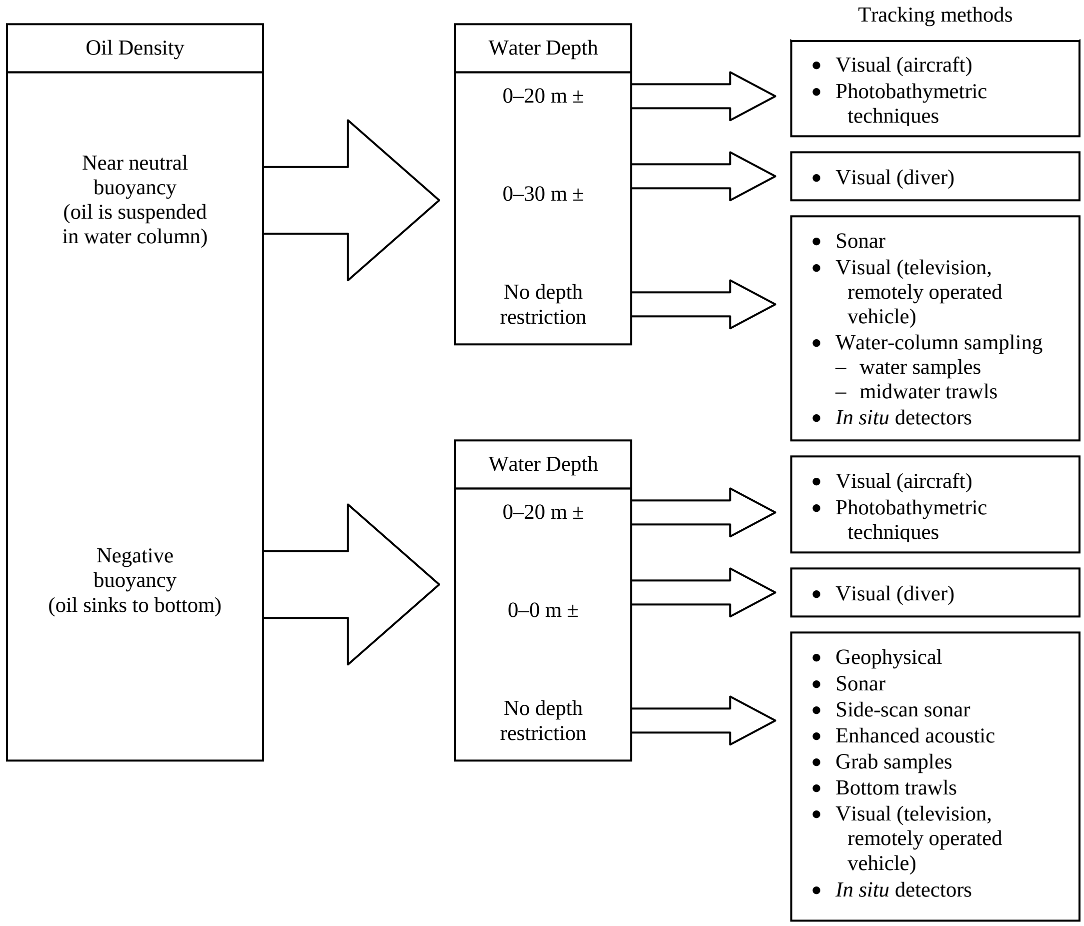


Figure E-1. Detection decision tree.

E.3 Recommendations for Detection

The technology and approaches have not changed since the National Research Council (NRC) report (Committee on Marine Transportation of Heavy Oils, National Research Council 1999). Experiences during spills for the period since the report have contributed to some better understanding. Decision-makers should still refer to the chart from Castle et al. (1995) and referenced in the NRC study (Figure E-1). Use of the V-SORS was refined during the spills of 2004 (Delaware River) and 2006 (Gulf of Mexico). Additional guidance includes:

1) Determine amount of impacted oil (oil that may contact or effect water inputs, sensitive areas, etc.) or recoverable oil.
    - Collectable amount is a function of time to reach the oil (including transit and mooring), capability of cleanup technique, weather and amount of storage available.
2) Try most simple method first that addresses amount of oil being detected.
3) Use sophisticated methods for deeper and larger amounts of oil. Use models if available to determine search area and potential amount of oil that may be recovered.

4) Make decisions based on the minimum amount of actionable oil (oil that may contact or effect water intakes, sensitive areas, etc.) or recoverable oil. This helps to define the resolution of the detection method needed.
   - Recoverable amount is a function of time to reach the oil (especially if offshore and mooring arrangements are made), capability of cleanup technique, weather and amount of storage available. For example, the amount of “recoverable oil” for the DBL-152 spill was 500 barrels? This was based on the cost for the recovery system to transit to the site, set up, and perform the recovery. It was also partially based on the amount of oil that was perceived to harm the environment or ultimately end up on shore.
5) Sonar can search a wide area but processing must be timely and resolution sufficient. Have vendors determine resolution (i.e., the size of the patch of oil that can be detected), amount of time to search any area, and the amount of time to process the data.
6) Operators of laser systems also need to define the area covered, estimated patch size, and the time to process the data.
7) Utilize differential GPS systems for finer search grids if available.
8) Minimize the amount of time between the detection and collection phases of the response.

E.4 Manual Detection Methods

E.4.1 Snare Sentinels

“Snare sentinels” can consist of any combination of the following: a single length of snare on a rope attached to a float and an anchor, one or more crab or lobster pots on the bottom that are stuffed with snare, or a minnow trap or eel pot stuffed with snare and deployed at selected water depths. The configuration depends on the water depth and where the oil is in the water column.

E.4.2 Vessel-Submerged Oil Recovery System (V-SORS)

The V-SORS consists of an 8 to10-foot pipe, 6 to 8 inches in diameter, rigged in a bridle fashion, attached with several 6 to 8 foot lengths of 3/8-inch or larger chain (Figure E-2). Around the chains, snare is tied. The system is towed behind a vessel and dragged along the bottom and somewhat angled through the water column. It is pulled up regularly and inspected for oil. The oil coverage on the snares is roughly estimated. The V-SORS Light system consists of a single chain with snare. This lighter system samples a smaller area but requires less logistics.

Figure E-2. The V-SORS used to search for and recover submerged oil.

APPENDIX F. VENDOR CONTACT INFORMATION

BioSonics, Inc.:	Robert McClure, MSc, FP-C Business Development 4027 Leary Way NW Seattle, WA 98107 bmcclure@biosonicsinc.com Phone: 206-782-2211 www.biosonicsinc.com
CodaOctopus Group, Inc.:	Anthony Davis President US Operations Bluewater House, 1601 3rd Street South, St. Petersburg, FL 33701 anthony.davis@codaoctopus.com Phone: 727-822-1565 www.codaoctopus.com
EIC Laboratories, Inc.:	Job Bello 111 Downey Street Norwood, MA 02062 bello@eiclabs.com Phone: 781-769-9450 www.eiclabs.com
RESON Inc.:	Mette T. Eriksen Consulting Project Manager 100 Lopez Road Goleta, CA93117 mette.T.Eriksen@reson.com Phone: 805-964-6260 www.reson.com
Science Applications International Corp.:	John T. Morris Marine Survey Manager 221 Third Street Newport, RI 02840 JOHN.T.MORRIS@saic.com Phone: 401-847-4210 www.saic.com

SRI International:	R. Timothy Short Chemical Sensors Group, Manager Marine Technology Program 333 Ravenswood Avenue Menlo Park, CA 94025 timothy.short@sri.com Phone: 727-553-3990 www.sri.com
Woods Hole Oceanographic Institution:	Dr. Richard Camilli Assistant Scientist Deep Submergence Lab Woods Hole, MA 02543 rcamilli@whoi.edu Phone: 508-289-3796 www.whoi.edu